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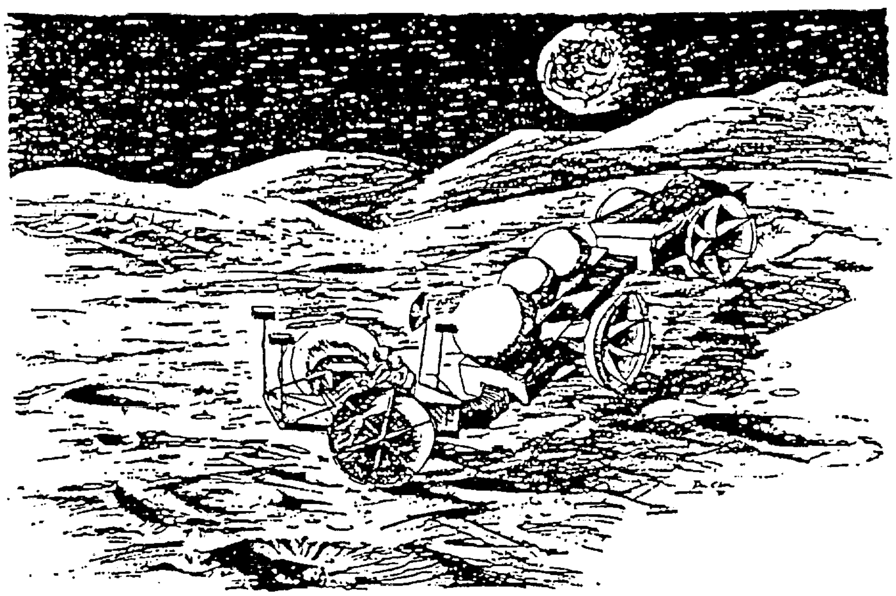
DESIGN OF A LUNAR TRANSPORTATION SYSTEM



Mechanical Engineering Students
FAMU/FSU College of Engineering, Tallahassee, Florida

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CONCEPTUAL SECOND GENERATION LUNAR EQUIPMENT

From

Introduction to Design Semester Projects
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1.0 Introduction

The Spring 1990 *Introduction to Design* class was asked to conceptually design second generation lunar vehicles and equipment as a semester design project. The following text is a brief summary of four of the final projects, followed by the original unedited reports in the appendices. Any questions concerning specifics should be answered by referral to the full reports.

The basic assumption made in designing second generation lunar vehicles and equipment was that a network of permanent lunar bases already existed. The designs were to facilitate the transportation of personnel and materials. The eight topics to choose from included flying vehicles, ground based vehicles, robotic arms, and life support systems. Two teams of two or three members competed on each topic and results were exhibited at a formal presentation.

The first report is on a lunar flying vehicle that uses clean propellants for propulsion. This report addresses a design that will not contribute to the considerable amount of caustic pollution already present in the sparse lunar atmosphere. It travels from specific point to specific point by way of ballistic flight techniques.

The second report addresses a second generation redesign of the current Extra Vehicular Activity (EVA) suit to increase operating time, safety, and efficiency. A separate life support system is also designed to be permanently attached to the lunar rover. The two systems would interact through the use of an umbilical cord connection. The umbilical cord could be disconnected once a destination is reached, allowing freedom of motion in the surrounding area.

The subject of the third report concerns designing a ground based vehicle which will travel for greater distances than a 37.5 kilometer radius from a base on the lunar surface. The vehicle is pressurized due to the fact that existing lunar rovers are limited by the EVA suits currently in use. The vehicle functions primarily as an exploratory vehicle, but the possibility of personnel transportation exists.

The fourth and final report concerns the design of a robotic arm for use at lunar bases or on roving vehicles on the lunar surface. The arm was originally designed as a specimen gathering device, but it can be used for a wide range of tasks through the use of various attachments. The robotic arm development involved considerations of harsh conditions, compactness, versatility, reliability, accuracy, and weight.

Summaries of each report can be found in sections 2.0 through 5.0, with the respective full reports located in the appendices.

2.0 A Clean Propellant Powered Lunar Flying Transport

The existence of lunar bases at different points of interest across the lunar surface would call for transportation means much more demanding than the original simple lunar rovers. A flying craft capable of traveling point to point distances in the range of 50-500 km is developed in order to shorten mission time and overcome inhospitable terrain. This report concerns the conceptual development of a cleanly fueled lunar flying vehicle to meet the second generation requirements of material and personnel transportation between lunar bases. The possibility of exploration of remote areas by the same craft is also pursued. Three basic modes of operation are performed by modifications made at the lunar bases. The final design was named the Multi-Purpose Flying Vehicle (MPFV).

2.1 Modes of Operation

A lunar flying vehicle should be designed to be as versatile as possible, and to perform a number of functions by means of modifications performed at lunar bases. The lower unit of the of the MPFV resembles a lunar lander design and remains the same for all modes. This unit contains the control, fuel, and propulsion systems for vehicle operation in all modes. The top sections are different for each of the modes. Through these modifications, the design should perform three basic functions: 1) the transportation of materials from a main base or depot to other bases or construction sites; 2) the transportation of personnel from base to base; and 3) the exploration of specific points on the lunar surface.

2.2 Propulsion Systems

The requirement of clean propellants effectively limited the choice of fuels and oxidizers to one combination. With the exception of cold jets and electrical propulsion, the hydrogen-oxygen reaction is the one of the cleanest forms of combustion known. Fortunately, the hydrogen-oxygen rocket engine also has one of the highest specific impulses known. The MPFV uses a centrally mounted LH2-LOX rocket for main thrust and oxygen cold jet rockets for stabilization during ballistic flight.

The production of lunar oxygen will drastically reduce the imported propellants for the MPFV because five-sixths of the combustibles by weight will be oxygen. The possible production of lunar hydrogen would further reduce the dependency on imported materials.

The hydrogen and oxygen are stored cryogenically as liquids in four sets of heavily insulated spherical tanks on the MPFV. The disadvantages of difficulty of cryogenic storage and handling are outweighed by the advantage of compactness, especially since a fully fueled MPFV would be 50% reactants by weight. Depending on loading and travel distance, the MPFV can use either two or four sets of symmetrically mounted tanks.

2.3 Conclusion

The MPFV represents a second generation conceptual design for a multi-purpose flying transport to operate on the moon during the years 2010-2030. The MPFV can be operated in three basic modes with conversions made at appropriately equipped bases. Cryogenically stored hydrogen and oxygen are used as fuel to reduce the emission of toxic materials. Transportation from point to point is accomplished through the use of ballistic flight techniques consisting of short bursts of power followed by long periods of free parabolic flight. Radiators are protected from dust during take-off and landing by the computer controlled closing of the radiators to seal them from contamination. A continuous link of communication is maintained at all times through the use of a system of satellites orbiting the earth and moon. Navigation is performed via a terrain tracking system which identifies surface features and compares them to stored data.

3.0 EVA Life Support System

The goal of the second generation EVA suit is to increase operating time, safety, and efficiency without sacrificing the flexibility and geometrical character of the current Extra Mobility Unit (EMU). The basic design addressed to meet this goal has three distinct parts: 1) the redesign of the current EMU life support system; 2) the adaption of an EMU oxygen rebreather and cooling system permanently affixed to a lunar vehicle; and 3) the interfacing of the two above systems to work in concert.

The new extended life support system will allow the crew member maximum flexibility and safety while performing extra-vehicular activities. The advantages of the suit for typical missions great distances from the lunar base are: 1) the crew members do not expend the EMU's consumables while riding in the lunar vehicle to and from a destination; and 2) a greatly decreased possibility of a system failure resulting in a fatality.

The new EMU design is basically a technological update of the current design's computer, oxygen delivery, and cooling systems. New features include the use of cryogenically stored oxygen, the ability to operate from an external Life Support System (LSS), liquid refreshment, and waste management.

3.1 System Redundancy

The safety of the crew member using the EVA suit is the primary concern of the life support system. A failure of one of the suit systems should not result in a life threatening situation. The linear architecture of the current EVA suit presents many such cases, even with the use if in-line redundancy. The new EMU design will correct this deficiency by using a doubly redundant Bi-Linear Cross Connect (BLCC) architecture developed for cave diving. Though this system is more complex, the use of improved technology and materials should allow the overall geometry of the existing system to remain the same. The improved system can be shown to be fourteen times less likely to have a failure that would cause a fatality.

3.2 Computer Controller

The current EVA suit uses an embedded micro-computer. The equipment was advanced at the time, but has become outdated in the rapidly advancing field of micro electronics. With the incorporation of cutting edge technology in the life support system, many advantages can be realized, and many difficulties can be overcome.

With these increased capabilities, it would be possible to perform many more functions than currently possible. The second generation EMU suit will run a diagnostic and corrective program continually to adjust for any problems with the suit or equipment.

The sensors used are important to any control system. With the reductions in size of electronic components, two sets of sensors can be used at each monitoring position. This

will assure that the control system is receiving correct information in order to respond without error.

3.3 Conclusion

The redesigned EMU suit incorporates double redundancy in both separate systems and computer controllers. Three on-board computers can be used with a 'majority rules' decision making process for diagnostic decisions during suit operation. A full manual operation mode can also be used if all control systems fail completely. The suit increases distance traveled and reduces chance of failures resulting in fatalities.

4.0 Pressurized Lunar Rover for Greater Distances

The goal of this project was to design a ground based vehicle which will travel for longer distances than a 37.5 km radius from a lunar surface base. The existing design is limited to a 37.5 km radius due to the limitations of current EVA suits. Designing the pressurized vehicle would eliminate these restrictions and would allow for much more comfortable operation in the vehicle. The manned vehicle would operate on a three day mission, traveling within a radius of 150 km at a speed of 10-15 km/h, with a four member crew. The primary function would be of an exploratory nature, involving experiments, photography, and computer analysis. Primary design considerations were structural, power, and control components.

4.1 Structural Design

The vehicle consists of a pressurized cabin which contains the life support for the crew members. It accommodates up to four crew members for an average mission time of three days. The cabin is cylindrical in shape with spherical end caps, both with a double wall construction. Insulation is used as a thermal barrier in the wall design. The material chosen for both the inner and outer walls is aluminum alloy 7075-T6. The windows are similar to those used on the space shuttle in that they consist of three separate structural members. A transparent film covers the outside glass and is periodically rolled over it in order to clear dust impaired vision, with the rolls of plastic to be cleaned at the lunar bases.

4.2 Power System

The power source used in the design is the Isotope Brayton Cycle, which transfers thermal energy into shaft work by turbines. The closed loop Brayton power cycle consists of four separate loop systems involving argon gas, sodium-potassium, freon, and propylene glycol. The isotope fuel may be either Pu-238, Po-210, or Cm-244. These isotopes can be packaged into convenient fuel modules which can be shielded to prevent crew exposure to radiation and configured to eliminate the possibility of combining into a critical mass. The power load is maintained at as constant a level possible by the use of battery arrays to even the load. The power system is transported in a separate trailer behind the main vehicle in order to reduce the dangers presented to crew members by this energy source.

4.3 Controls

The steering mechanism is simplified by changing the ratio of adjacent wheel rotation in order to change direction. This reduces both the number and complexity of steering and suspension components.

Communication with the lunar base is of utmost importance during the average three day mission of the vehicle. Since lunar nodes will have been established, these satellites will be used to relay signals using direct radio and computer monitoring. The vehicle's antennas will be located at the rear to communicate with both lunar bases and earth.

4.4 Conclusion

The first goal of the second generation pressurized lunar rover will be to establish itself on lunar bases and to develop a data base on the lunar surface such that the accuracy of the topographic mapping can be confirmed for future development of unmanned missions. Based on present studies, the lunar vehicle will be feasible, but further development and research is needed to verify assumptions.

5.0 Robotic Arm Design Project

This project represents a group effort to explore the possibility of deploying a robotic arm on the moon. The arm was originally conceived as a specimen gathering device to be fitted on a lunar vehicle, but it has been revised to satisfy a wider range of tasks. The design of the Extendable Robotic Collection System (ERCOS) incorporates key issues of compactness, versatility, reliability, accuracy, and weight. The arm can be used on both lunar vehicles and at lunar bases for a variety of functions.

5.1 Arm Structure

The robotic arm is composed of 9 links and attains 6 degrees of freedom. It combines the concepts of both revolute and cylindrical robots. A telescoping tower assembly is used for the majority of the arm's movement with revolute and cylindrical joints at the extremity for detailed motion. The telescoping assembly has the ability to collapse into a compact sealed structure when the arm is not in use. The material used throughout the arm is aluminum 2014-T6. With the material and structure known, computer modeling was then used for stress and deflection measurements.

5.2 Computer Modeling

A test loading of 500 newtons was used during computer modeling to represent the maximum possible loading encountered by the ERCOS system. The maximum static loading called for is 250 newtons, but the computer analysis was performed for static loadings and a 500 newton static load simulated the forces that would occur when the load mass was accelerated. A PAL2 computer analysis was used to determine the minimum thickness of tubes used in the telescoping lattice structure. Deflections at the ends of the links in the fully extended position were also calculated.

5.3 Environmental Considerations

The environmental condition that would have the greatest effect on the ERCOS system would be the variation of temperatures causing expansions and contractions. This problem is overcome by placing thermal sensors at even increments along the links and using their output in the controller program to actively compensate to assure positional certainty.

Lunar dust presents a formidable problem in the case of any exposed mechanism on the lunar surface. It is extremely important to completely cover the joint actuators to exclude lunar dust. Nylon bushings are utilized to seal link shafts. The structure can be retracted and sealed when not in use to protect from contamination.

5.4 Conclusion

The ERCOS system is a direct descendant of the robotic arm on the Viking lander used on the surface of Mars. The primary mission of the ERCOS design is similar in the respect of soil gathering operations, but it can provide a wide range of services to both stationary and mobile platforms. Different end effectors can be used with the basic robotic arm to provide the different functions as needed.

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APPENDIX AA

FINAL REPORT
A CLEAN PROPELLANT POWERED LUNAR FLYING TRANSPORT

Group members

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For

INTRODUCTION TO DESIGN
EML 3541

submitted to

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Submittion date: 4/21/90

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A CLEAN PROPELLANT POWERED LUNAR FLYING TRANSPORT:
The Multi-Purpose Flying Vehicle (MPFV)

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1.0 Abstract

Development of a permanently manned lunar base would be the next logical step in the exploration of space. The purpose of the Surveyor and Apollo landings of the sixties was to answer the many questions concerning lunar materials, properties, and conditions as well as feasibility of further exploration. One of the more important positive discoveries was the relatively large percentage of oxygen (40%) contained in the form of oxides and other various compounds in the lunar soil. The production of oxygen from the regolith has been deemed possible by technology of the near future and could, quite literally, fuel the further exploration and colonization of the moon. Lunar bases and transportation systems could be made an economic reality with the use of these and other lunar resources. Pollution of the sparse lunar atmosphere is also a primary concern in the colonization of the moon.

A single manned lunar base for the purpose of evaluation of possible techniques of sustaining life with limited imported materials and supplies through the use of advanced mechanical and biological methods would represent the transitional phase to the second generation technology. The expansion of this single base into a network of lunar bases practicing the notion of self sufficiency would constitute the dawn of second generation lunar technology.

A CLEAN PROPELLANT POWERED LUNAR FLYING TRANSPORT:
The Multi-Purpose Flying Vehicle (MPFV)

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Submittion date: 4/21/90

2.0 Introduction

The existence of lunar bases at different points of interest across the surface would call for transportation means much more demanding than the original simple lunar rovers. Various studies have indicated that ground transportation techniques become rather uneconomical when the involved distances traveled exceed 50 km. At a recommended maximum speed of 20 km/h, the mission time and fuel consumption involved become prohibitive, not to mention the possibility of terrain inhospitable to conventional surface vehicles. A flying craft capable of transportation distances in the 50 to 500 km range should be developed. The obvious savings in time would be realized for the entire range of travel, and in the cases of greater distances, savings in fuel could be realized. This report concerns the conceptual development of a cleanly fueled lunar flying vehicle to meet the second generation requirements of material and personnel transportation between lunar bases. The possibility of exploration of remote areas by the same craft is also pursued.

3.0 Design Specifications

The development of any transportation system is strongly influenced by its surroundings. The conditions on the lunar surface present a very formidable challenge to the designing engineer specifying such a system. The following environmental factors represent the basic factors affecting the development of a flying vehicle.

- The Moon's gravity is one-sixth of that found on Earth.

- There is no atmosphere to speak of. All equipment will be exposed to a harsh vacuum. There is no heat convection. The light is not scattered by the sparse atmosphere and sharp dark shadows result with various optical difficulties such as glare, back-lighting, and washout.

- Meteorites are not slowed or vaporized, resulting in particles impacting machinery at velocities of 2.4 - 72 km/s.

- The surface temperature of the Moon varies greatly, approximately plus or minus 150° C, with steep thermal gradients of 5° C/hr.

- Solar radiation strikes equipment with full force.

- The lunar surface contains a very fine abrasive dust that makes lubrication difficult.

- All communications are by line of sight.

- The moon follows a cyclic pattern of 14 earth days and 14 earth nights.

A list of design specifications can be found in Table A1 - Appendix A, detailing all of the conditions considered in the conceptual design. The essential design specifications are shown in Table 1.

No	E/O	SPECIFICATION	COMMENT
1	E	Capacity to carry 6 astronauts in shirt sleeve operating conditions	Transportation from base to base
2	E	Capacity for carrying cargo	construction scientific equipment etc.
3	E	Life support	air regulation,climate control
4	E	Efficient Thrust System	High Specific Impulse Rating
5	E	Constant communication with base	problems arise past line of site
6	E	Heat Rejection System	climate control,electrical,engine
7	E	Clean Propellants	LOx LH
8	E	Radiation Sensors	Able to detect before main dose
9	E	Sufficient range to justify flying	50-500 km rover for short trips
10	E	Electrical system sufficient for navigation, life support,communication,vehicle control	10 kW
11	E	Fuel capicity for range	500 km
12	E	Navigation system	Terminal (50m), landing[illegible]

Table 1, Essential Specification List

4.0 Alternative Designs

There were several alternative overall designs studied during the decision process, they were as follows:

- Near surface transport
- Medium altitude maneuverable craft
- Long range ballistic design

The near surface transport would have been a relatively small craft that flew at several meters above the lunar surface. The design would carry a relatively small amount of personnel or materials, the speed and maneuverability being most important. The transport would also have the capability to hover near the surface. The basic function, as far as materials and personnel, of the transport would be similar to that of rover designs. The near surface transport would have been much faster than the rovers, but would have been limited in the cargo capabilities. The near surface transport would also have been very susceptible to lunar dust infiltration in vehicle components.

The medium altitude maneuverable craft would have the *motion* characteristics of a helicopter, in that it would have the ability to fly at heights of 100-1000 meters. It would be resistant to dust while in route to a destination, but could still have problems at the take-offs and landings. The need for instantaneous changes in direction would require large engines and a low weight, thereby reducing the cargo capacity.

The long range ballistic design would use relatively short bursts of power to accelerate and decelerate upon take-off and landing. A parabolic trajectory would be followed with long periods of free-fall flight. The ballistic design would have long range capabilities and large cargo capacities. The entire flight would require a great deal of preparation in order to go from one point to another distinct point on the lunar surface with minimum corrections [2].

The possible solutions for the basic subsystems of the above alternative designs can be found in Table B1. This table contains solution alternatives for each subsystem function of such a vehicle. The basic systems are as follows: propulsion, propellant, power, heat rejection, EVA suits, navigation, and communication.

5.0 Optimal Conceptual Design

The problem at hand is to design a lunar flying vehicle that uses a clean propellant as its source of propulsion. The concern with lunar pollution stems from the fact that a fair percentage of the present lunar atmosphere can be attributed to the waste products of the Surveyor and Apollo missions [5]. The Apollo missions used hypergolic propellants (nitrogen tetroxide and Aerozine 50) in engines pressure fed by liquid helium in both of the stages. Both the exhaust and reactants are toxic and react unfavorably with many

materials and components. Clean propulsion is just one of many requirements for the design.[a]

The major requirements were used to compare the three possible designs in a weighted property index table.[b] The design that presented the highest satisfaction value was the long range ballistic design. The ballistic design had the advantage of increased cargo and economy, along with dust resistance. The final design was named the Multi-Purpose Flying Vehicle (MPFV).

The MPFV is designed to address the problems of inter-base transportation and exploration with clean burning propellants. A lunar flying vehicle should be designed to be as versatile as possible, and to perform a number of functions by means of modifications performed at lunar bases. The lower unit of the MPFV remains the same for all modes, Figure C1 (Appendix C) shows two views of the lower unit. This unit contains the control, fuel, and propulsion systems for vehicle operation in all modes. Through these modifications, the design should perform three basic functions: 1) the transportation of materials from a main base or depot to other bases or construction sites, 2) the transportation of personnel from base to base, and 3) the exploration of specific points on the lunar surface.

The original research station should eventually grow into a production facility during second generation colonization [5]. Any materials or supplies will need to be delivered to secondary bases at distant locations. If the original lunar base is used as a gateway to colonization, personnel will have to be transported across great distances to the newer bases. Specific points on the lunar surfacę will still need to be accessible, even after the establishment of a network of lunar bases. Rough, distant regions such as remnant volcanos will provide valuable information on the composition of the inner crust and possibilities of economic exploitation of the minerals. The possibility of instrument setups on the opposite side of the moon to detect radio waves from deep space without interference from the Earth could be realized.

The basic structure of the MPFV is not unlike that of the lunar lander used during the Apollo missions.[c] The fundamental difference between the two is the fact that the lunar lander was designed to be disposable and one shot only, whereas the MPLV is designed with an expected life span of ten years or more. The same basic suspension is used with sealed spring loaded shock absorber to allow for a smooth landing without suspension damage. Figure C3 depicts the suspension design. A single centralized main engine is incorporated with four clusters of stabilizing rockets mounted outwardly to control orientation. The rockets, suspension system, and fuel tanks comprise a majority of the lower portion of the craft. The central section is for crew and passengers or cargo. The radiators are attached to the top of the craft, along with various components of the communication and navigation systems. A detailed breakdown of the various systems covered to date will be addressed

[a] see Appendix A.

[b] see Appendix D.

[c] see Appendix B.

in following sections.

The conversions of the MPFV are to be done at the main base which is assumed to have certain facilities and equipment capable of dust removal, heavy lifting, and cleanroom conditions. The vehicle will have components that can be removed as sections and serviced in a cleanroom.

In the personnel transportation mode, a short cylindrical pressurized vessel would be affixed to the central portion of the MPFV, as seen in Figure C2a. All oxygen and air purification equipment, along with climate control heat exchanger, would be an integral part of this pressurized section. The communication and heat radiation section would then be attached to the top of the vehicle. The modifications could be affected in minimum time through the use of compressed air or liquid powered tools used by workers in EVA suits. The section would have an airlock door accessible by pressurized docking vehicles at each base.[a]

The conversion for payload transportation is affected in the same general way at a base, see Figure C2b. In this case, the central section is comprised of a relatively light structure to support the upper communication and heat rejection equipment with payload cages on either side of the two operators in EVA suits located in the center of the section. Holographic heads-up displays will be incorporated into the EVA suit helmets in order to eliminate controls that could be contaminated by dust. Many controls could be executed through the use of voice commands which should be possible by the technology of the time. The actual in-flight movements will be controlled by computer sequences with manual override possible with basic controls available to the operators in the form of easily articulated levers and pedals. This setup allows the MPFV to carry much cargo by the virtue of the large amount of space made available and the large amount of weight removed by the replacement of the pressurized section with the light frame payload section.

The exploration mode is basically similar to the payload transportation mode with the exception that the cargo cages are removed and additional equipment is added for experiments and sampling. A representative diagram can be found in Figure C2c.

The MPFV would weigh approximately 20 metric tons dry, and would have to hold up to 20 additional metric tons of fuel for the top payload travel of 500 km [4]. The flight time would be about 15 minutes one way for the 500 km flight and 5 minutes one way for the 50 km flight. The required velocity for the 50-500 km range would be 280-840 m/s. The maximum altitude would range between 12 km and 116 km for the travel range. The 200,000 N thrust main engine would subject inhabitants to an acceleration of 3.4 m/s^2 vertically, well within the comfort range.

The following basic systems will be discussed, as covered to date in the development of the MPFV design: propulsion, propellant, power, heat rejection, controls, EVA, radiation protection, materials, lighting, suspension, navigation, and communication.

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[a] see Appendix E.

Systems and Components

Propulsion

The requirement of clean propellants effectively limits the choice of fuels and oxidizers to one combination. With the exception of cold jets, the hydrogen-oxygen rocket engine is the cleanest form of combustion known. The hydrogen-oxygen rocket engine has one of the highest values for specific impulse, defined as the time during which a propellant can deliver a force equal to the propellant's initial weight. In the case of flight vehicles, this is an all important parameter due to the desire to maximize efficiency and minimize weight. Second generation engines should be capable of specific impulse values in the range of 485 seconds [7]. Due to the required mixture ratio of approximately five to one, certain undesirable byproducts will be formed, such as hydrogen peroxide and ozone, both of which are toxic to humans. These are assumed to be in small concentrations compared to the water vapor produced.

The production of lunar oxygen will drastically reduce the imported propellants necessary for the MPFV, considering five-sixths of the combustibles will be oxygen by weight. The main central engine will be larger than that of lunar landers, due to the increased payload requirements. The main engine would have a full throttle thrust of 200,000 N and could be throttled down to 10%. The directional thrusters would provide orientation control during the flight and would consist of cold jet nozzles using oxygen as a propellant. The main engine would not be gimbal mounted but solidly attached to the frame through vibrational isolation mounts.

Cooling of the main engine would be in the form of both active and passive cooling techniques. The process of circulating liquid hydrogen through the rocket cone and chamber to remove heat is imperative in applications such as these. Both propellants are stored cryogenically as liquids, with further details given in following sections. The circulation of liquid hydrogen through the cone and chamber walls serves a dual purpose, first being the vaporization of hydrogen prior to combustion and second, the absorbtion of great amounts of heat through this phase change [1]. Other active cooling methods for the engine can be used in the heat rejection system which is discussed in following sections. Passive cooling techniques can be used in the form of plates to remove heat from sensitive components of the engine.

Propellants and Storage

Even though the choice of propellants has been made for the MPFV, there are several ways of storing them. Hydrogen and oxygen can either be stored as a pressurized gas or as a liquid with extensive thermal protection. A cryogenically stored liquid offers the advantage of compactness but increases difficulty of storage and handling. The same characteristic of high heat conduction for liquid hydrogen that made it desirable for active

cooling techniques in the rocket engine makes it difficult to protect from boil-off. These problems should be overcome by advanced technology and the advantages of a greatly reduced tank size will be realized. Fuel is stored cryogenically on the MPFV.

The propellant tank setup for the MPFV involves four sets of spherical hydrogen and oxygen tanks arranged symmetrically on the lower portion of the craft. Depending on the loading and travel distance, the MPFV can run on either two or four sets of tanks. All four sets could be removable for servicing at the lunar bases, or could be serviced on the craft.[a] A pump system could facilitate balancing the MPFV depending on the loading prior to take-off and landing. This would allow for the minimization of moments created by the main engine during burns and reduction of the amounts of oxygen expended in the cold jet stabilizers.

Approximate tank sizes can be calculated from a rough estimate of fuel requirements for a 500 km flight at a maximum cargo capacity of 1500 kg (considering all equipment changes between modes). For this case, the MPFV would weigh 20 metric tons dry and have four sets of tanks containing 20 metric tons of propellants. Using general values of 1000 kg/m^3 and 70 kg/m^3 for the densities of cryogenically stored liquid oxygen and liquid hydrogen respectively, it is found that each oxygen tank would be 2 meters in diameter and each hydrogen tank would be 2.8 meters in diameter. Any additional fuel required for a power system would be assumed negligible compared to the fuel requirements for propulsion. All calculations are based on round trip conditions.

Power System

It has been stated that fuel cells are a favorable source of power if a hydrogen-oxygen propulsion system is used due to the fact that the masses of additional tanks would be unnecessary. The water produced could be stored and used in the heat rejection system. There are basically three systems to consider for power in the MPFV: 1) batteries, 2) solar energy, 3) fuel cells [4]. The amount of power is assumed to be approximately 10 kW, including the lighting and heating system if the craft is used during the long lunar night. The mission time should always be in the 10 hr range for exploration mode, and the 30 minute range for personnel and materials transportation mode.

One of the better choices for batteries would be the high density rechargeables of the lithium metal sulfide type, which offers one of the lowest kilogram per kilowatt-hour ratings available at 9.1 kg/kwh. For a mission of 10 hours, the batteries alone would have a mass of 900 kg, this would be considered excessive in the case of a flying vehicle.

Photovoltaics are a desirable choice of power for bases, considering the availability of unimpeded solar energy. For use on any vehicle, a backup battery system would be required for operation during the lunar night and the weight constraint would again be introduced. Lunar dust would also cause problems with the solar array operation. All of

[a] see Appendix E

the above considerations aside, gallium arsinide PV cells would be a good choice if solar power were to be used. Assuming a 1400 W/m^2 solar flux and 18% efficiency, it is found that 20 square meters of solar cells are required at a mass of 250 kg. The size of the solar array would also prohibit the use of this system.

New fuel cell technology could be implemented on the MPFV. The assumption of 0.4 kg per kilowatt-hour can be made by today's standards for electrical production by such technology. A ratio of 8:1 oxygen to hydrogen (by weight) would imply that 4.4 kg of hydrogen and 35.5 kg of oxygen would be required for a 10 hour trip requiring an average 10 kW of power. The fuel cell and assorted hardware would have an approximate mass of 150 kg. All things considered, the new fuel cell technology would be used in the MPFV.

Heat Rejection

An active thermal control system is needed to reject heat from the propulsion, power, and avionics systems as well as solar energy absorbed. The MPFV would use two active heat rejection systems for operations, one being radiators and the other flash evaporators. The radiators would be used in normal steady operations and the flash evaporators in the event of sudden loads requiring immediate heat rejection, such as firings of the main engine.

In the operation of the flash evaporators, water is vaporized on an internal heat exchanger and vented to the outside of the craft. The vaporization absorbs and removes heat at a rapid rate due to the high heat of vaporization of water. The stored water would be continually supplemented by the operation of the fuel cells.

The radiators would be located, as previously stated, on the upper portion of the MPFV along with communication systems. The radiation panels could be opened and closed at will, depending on the conditions around the craft. The radiators would be open to reject heat at all times, with the exception of take-off and landing. At these times, there would be a large amount of dust ejected from the surface and the highly cohesive dust would adhere to the radiators if they could not be protected. The radiators would then absorb heat instead of rejecting it. The sealable radiators reduce this effect. A single loop cooling system would be used as it would reduce the number of parts considerably when compared to a dual loop system.

Double wall protection can be used in the pressurized compartment when the MPFV is in personnel transport mode. The external wall would be supported from the inside by carbon fiber constructions to reduce weight and heat conduction. Extensive use of these and other passive heat rejection systems such as thermal blankets and isolators would reduce the weight of the entire cooling system considerably. Passive materials such as directional insulation can be used to remove heat from sensitive components in the vicinity of the engine.

Communications

An essential feature of any manned excursion away from base is a continuous communication link. In the event of an emergency situation, the astronauts must be able to reach the base for help. The system proposed here is recommended by the Office of Space Operations. It consists of two lunar satellites and two earth satellites. When on the far side of the moon, at least one of the lunar satellites will be visible for most sites. On the near side, at least one earth satellite will be visible.

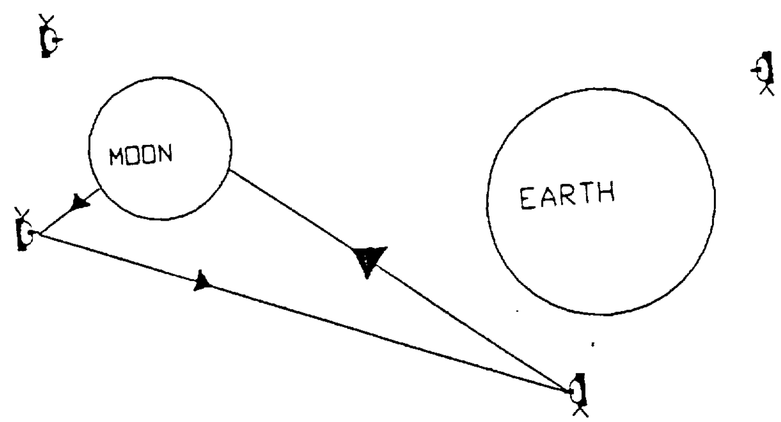

Figure 1, Geometry of Communication System

As seen in Figure 1, a communication path from nearly any location on the lunar surface to another or to Earth is accessible by a series of relays across various satellites. To allow for high definition stereo cameras with a high frame rate, a 200 Mbps transmission rate is needed. The longest transmission from the near lunar surface to earth requires an antenna of 1.5m and a power availability of 125W . This high power requirement is a potential source of problems due to the limited weight of the vehicle. Therefore, the only time it is recommended to use the cameras is in the exploration mode when the vehicle is stripped down and more space is available for extra electrical power generation. The second problem which exists with this system is the existence of regions where the signal is not transmitted effectively. The problem areas are the rim separating the far and near side, and the polar regions.[13] Since the problem is inherent in the geometry of the system, no simple solution exists. The height at which the vehicle travels will eliminate some problems, ground based operation of the vehicle should recognize this shortcoming and be prepared for it.

Radiation

Due to the moon's lack of a uniform magnetic field, high levels of radiation are sometimes present on the lunar surface. [11] Adequate protection of human life is a must for

any design considered. The only way to limit the amount of radiation involves the use of shielding. However, since the vehicle is constrained to a relatively low weight, extensive shielding is not a solution. Rather, the vehicle will take full advantage of its speed capabilities and transport the astronauts to a shelter. The ability to do this hinges on being able to accurately predict a life threatening radiation event. From earth based observatories, it is possible to predict the likelihood of a high influx of radiation . Usually, a 1-4 hour warning is given before the particles reach the earth-lunar region. Eight hours after these particles have been confirmed, the maximum dose will arrive.[11] To prevent the astronauts from dangerous radiation levels a communication link with a radiation information source is kept open at all times. In addition, a radiation survey meter will be onboard providing a continuous radiation level signal..[2]

Navigation

A lunar flying vehicle presents a serious navigation problem. Since the vehicle has a projected range of 500 km, coverage will be needed over a long range as well as accuracy in landing situations. The most important consideration of a navigation system is accuracy. In order for the system to effectively identify the vehicles location, an accuracy of 100 m is needed for any distance greater than 1 km from the base. For landing during the lunar night, the astronauts will depend almost entirely on the navigation system for guidance. To safely perform this task, a landing accuracy of 1 m is needed.[10] A second very important consideration of the system is the difficulty in the setup of the system. Due to the remote location and the limited resources available, effective tracking systems used on the Earth are not easily relocated for lunar use. Other considerations are the systems ability to cover the range the vehicle travels in, and the mass of material that needs to be transported from the Earth. Several systems were considered and evaluated using the weighted property index shown in Table 2.

	Range	Accuracy	Set up	Mass	Total
Lunar Orbit Satellite	14 / 100 / 5	25.8 / 60 / 3	0 / 0 / 0	8.4 / 60 / 3	48.2
Low Frequency LORAN	11.2 / 80 / 4	25.8 / 60 / 3	11.6 / 40 / 2	0 / 0 / 0	48.6
Surface Based Radar	2.8 / 20 / 1	34.4 / 80 / 4	17.4 / 60 / 3	5.6 / 40 / 2	60.2
Terrain Matching	11.2 / 80 / 4	43 / 100 / 5	11.6 / 40 / 2	11.2 / 80 / 4	77

Table 2; Weighted property index table for navigation systems used on the lunar surface

The system chosen for use on the MPFV was the terrain matching radar. Currently used as the guidance system on Cruise missiles, the system offers near landing accuracy navigation over the entire lunar surface. The system works by identifying distinct features on the surface as the vehicle travels over them. These features are then compared to surface feature maps stored in the systems memory and an orientation is determined. Near the base transponders are set up to ensure the accuracy necessary for landing. One problem with this system is its dependance on the accuracy of the maps available.[10] By the second generation, however it is expected that the surface features will be well known.

6.0 Conclusions

The MPFV represents a second generation conceptual design for a multipurpose flying transport to operate on the moon during the years 2010-2030. The MPFV can be operated in three basic modes: 1) material transport, 2) personnel transport, and 3) exploratory vehicle. Basic conversions are done at appropriately equipped base facilities.

Cryogenically stored hydrogen and oxygen are used as fuel to reduce the emission of toxic materials. Main thrust is provided by a central solid mount hydrogen-oxygen rocket that is pump fed and incorporates an active cooling system. All orientation control is through the use of oxygen cold jet thrusters.

Transportation from point to point is accomplished through the use of ballistic flight techniques of short bursts of power with long periods of free parabolic flight. Radiators are protected from dust during take-off and landing by computer controlled closing of the radiators to seal them from contamination. Rapid cooling is done through water evaporators. Fuel cells are used to provide electrical power to the control system during operation and water produced goes into storage for water evaporators.

A continuous link of communication is kept open at all times through a system of satellites orbiting both the Earth and Moon. Navigation is performed through a terrain tracking system which identifies surface features and orients the MPFV according to mapped data.

The MPFV addresses the needs of second generation lunar transportation with an emphasis on environmental concerns.

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[10] *Lunar Base Launch and Landing Facility Conceptual Design* , Eagle Engineering, March 25, 1988.

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APPENDIX A

No	E/O	SPECIFICATION	COMMENT
1	E	Capacity to transport 6 astronauts in shirt sleeve operating conditions	Transportation from base to base
2	O (med)	Capacity for carrying cargo	construction scientific equipment etc.
3	O (maj)	Small enough for feasible delivery	broken down or collapsed -low weight
4	O (med)	easy to enter and exit	Accounts for pressurized suits
5	O (min)	ability for ground base motion	Can taxi to launch spot
6	O (maj)	Energy saving launch mechanism	something to overcome inertia
7	E	Clean Propellants	LOx - LH
8	O (min)	Ability to obtain escape velocity	2.4 km/s
9	E	Sufficient range to justify flying	50-500 km rover for short trips
10	E	Structure handles inertial forces of landing and propulsion	materials, vibration force control structure configuration
11	E	Efficient thrust system	High specific impulse rating
12	E	Efficient electricity system	weight,power favorable,life span
13	O (maj)	Emergency fuel system	back up for passenger saftey
14	E	Heat rejection system	heat dissipation for electrical heat climate control,propulsion heat
15	E	Fuel storage sufficient for range	50-500 km
16	E	Electrical system sufficient for lighting navigation communication	10 Kw
17	E	Radiation sensors	able to detect in before danger
18	E	Navigation System	1m accuracy close to base
19	E	Constant communications with base	problems arise past line of site
20	E	Life Support System	Air ,Climate control, Radiation
21	E	Reliable operation	assure return to base
22	E	Back up Systems	triple saftey for life dependant

Table A1, Detailed Specification List

No	E/O	SPECIFICATION	COMMENTS
23	O (med)	micro-meteroite protection	shielding or shelter
24	E	protection from dust	radiators.bearings
25	E	protection from large temperature change	exterior systems
26	O(min)	quick jetison of nonessential weight	empty tanks
27	O(med)	wide range of vision	able to view directly below
28	O(med)	retaining system for loose objects	velcro.bunge cords.nets
29	E	exterior lighting system	night use
30	E	materials -low weight high strength -low thermal expansion -impervious to vacuum -unaffected by intense uv rays -can handle temperatures	major considerstions are the transport cost. the conditions on the lunar surface safety, and the life expectancy
31	O(maj)	simple routinely performed maintence	keep in good condition
32	E	accounts for no air	no pressure
33	E	minimize polution	minimize expectorants

Table A1, Detailed Specification List (Cont)

APPENDIX B

	A	B	C	D
Propulsion	Chemical Rockets	Electric	Nuclear	
Prpoellants	Hydrogen Oxygen	Solid Fuel	Hydrazine	Nitrogen Tetroxide Aerozine 50
Propellant Storage	Liquid Form	Highly Pressurized	Solid	
Electrical Power System	Nuclear	Batteries	Solar	Fuel Cell
Heat Rejection	Radiators	Water Vaporizer	Ammonia Boiler	
Communication	Lunar Satellites	Direct Transmission line of sight	Lunar and Earth System	
Navigation	Terrain Mapping	Satellite Tracking	Lunar Based Radar	LORAN
Life Support	EVA suit	Pressurized Cabin		

Table B1, Solution Alternatives

APPENDIX C

LOWER VEHICLE ASSEMBLY

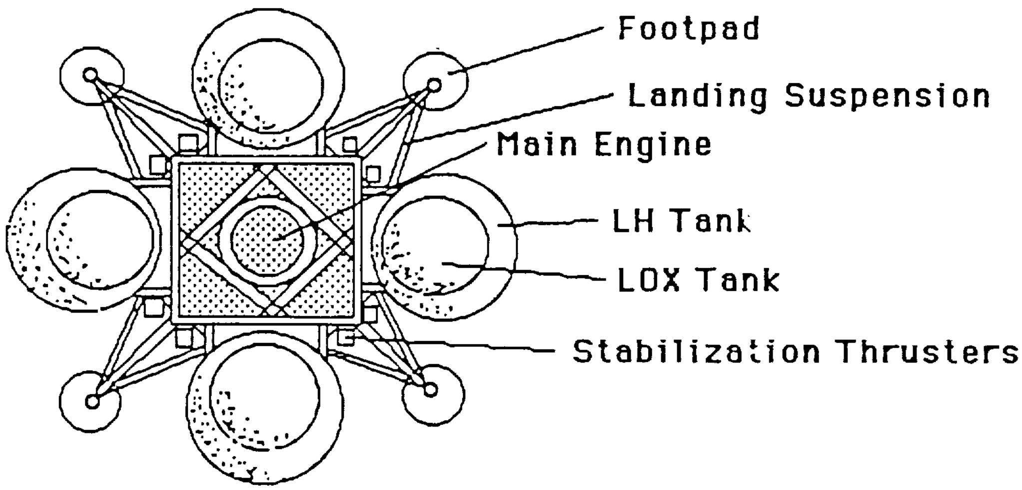

Fig C1a: LOWER ASSEMBLY TOP VIEW

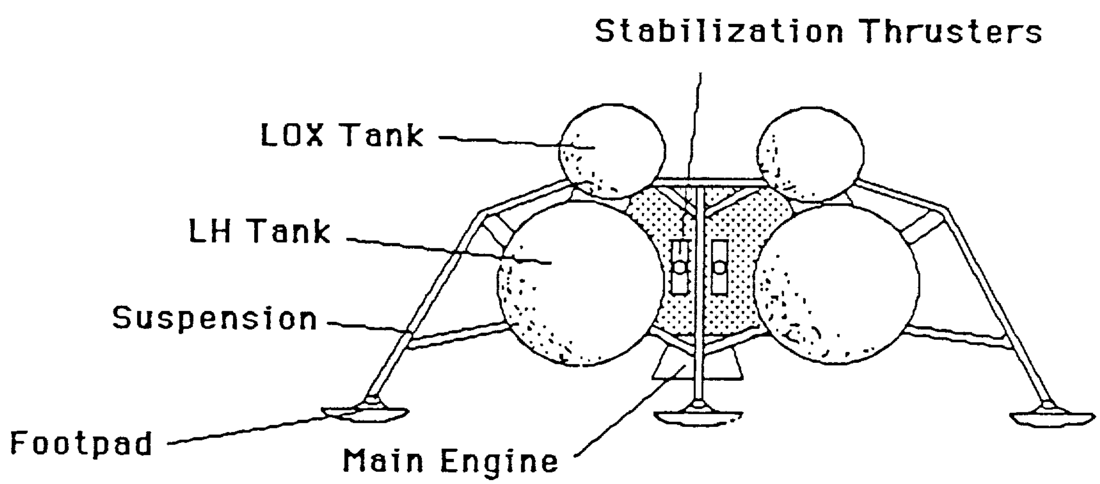

Fig.C1b LOWER ASSEMBLY SIDE VIEW

VEHICLE MODE VARIATIONS

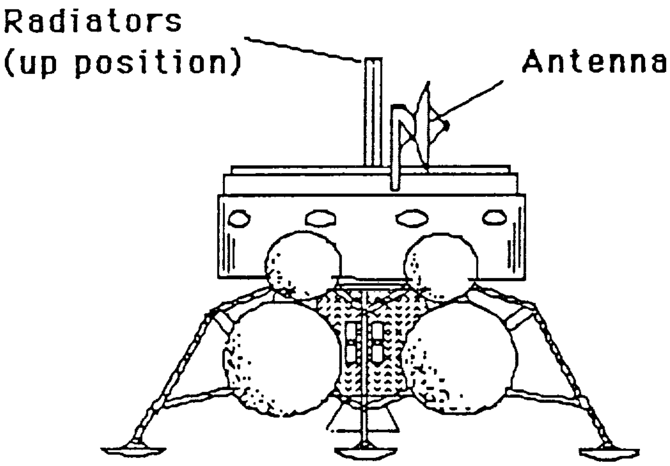

Fig. C2a:
MPFV IN PERSONNEL MODE
(PRESSURIZED CHAMBER)

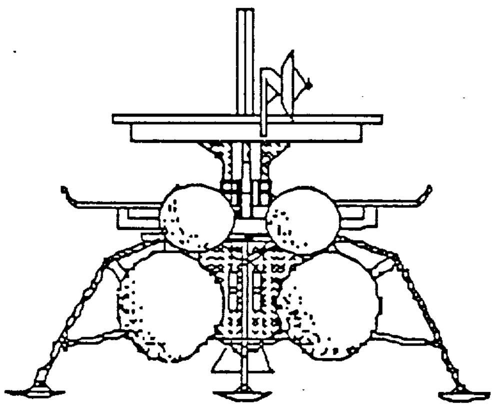

Fig. C2b:
MPFV IN MATERIAL TRANSPORT
MODE (OPEN, EVA REQUIRED)

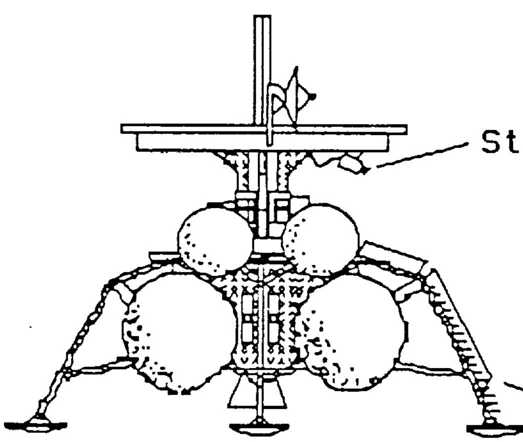

Fig. C2c:
MPFV IN EXPLORATORY MODE
(OPEN, EVA REQUIRED)

SUSPENSION COMPONENTS

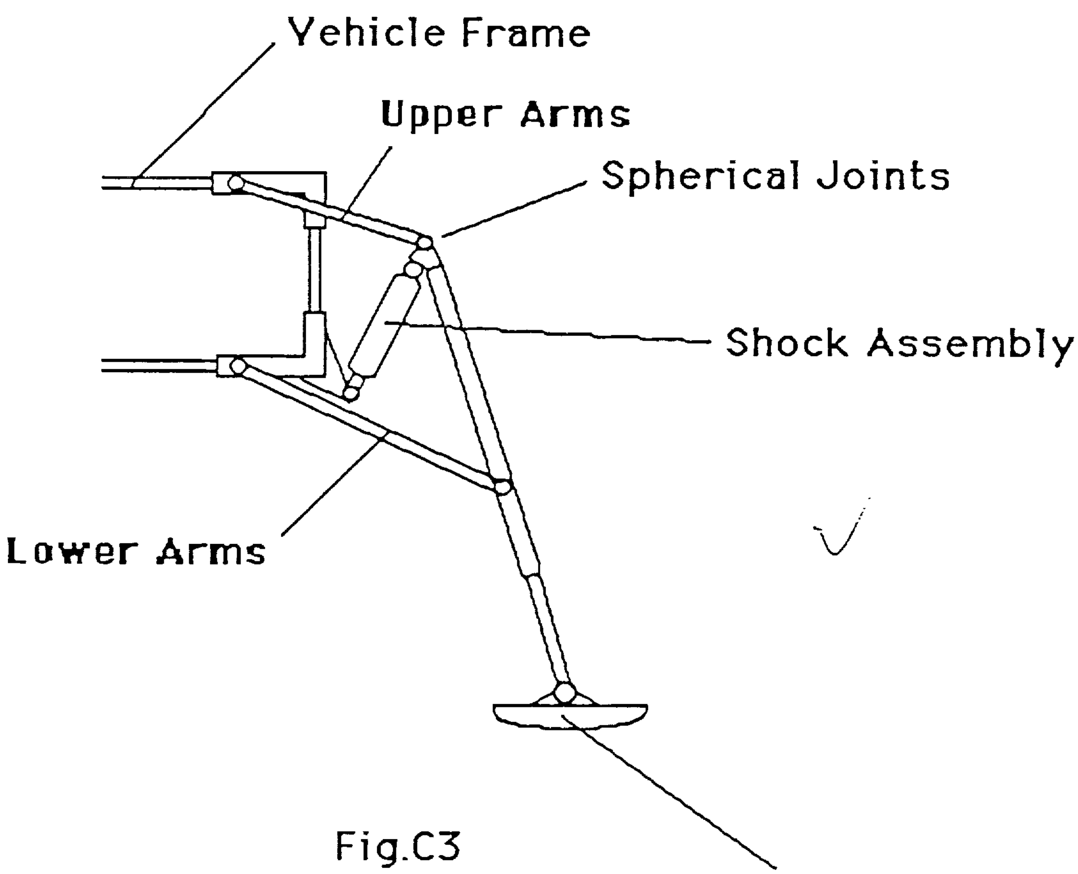

Fig.C3
SUSPENSION

APPENDIX D

	Range .22	Manuverability .11	Fuel Efficiency .33	Cargo .11	Dust Scatter .22	Total
Near Surface Transport	8.8 / 40 / 2	6.6 / 60 / 3	8.25 / 25 / 1	4.4 / 40 / 2	0 / 0 / 0	28.05
Manuverable Craft	8.8 / 40 / 2	4.0 / 100 / 5	16.5 / 50 / 2	4.4 / 40 / 2	11 / 50 / 2	44.70
Ballistic Design	22 / 100 / 5	6.6 / 60 / 3	33 / 100 / 4	11 / 100 / 5	22 / 100 / 4	94.60

Table D1, Weighted Property Index for Craft

APPENDIX E

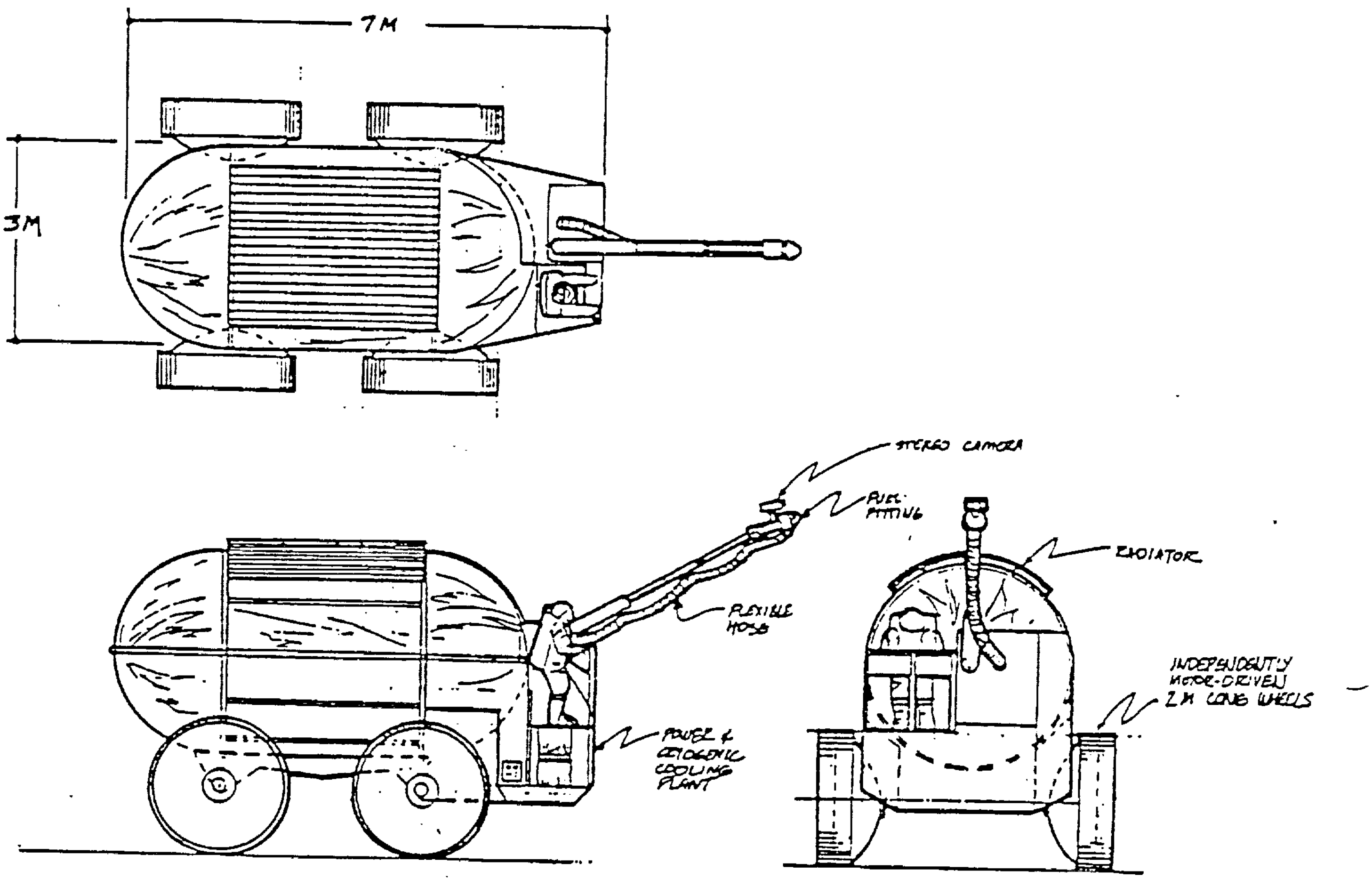

Figure E1, Propellant Refill Vehicle

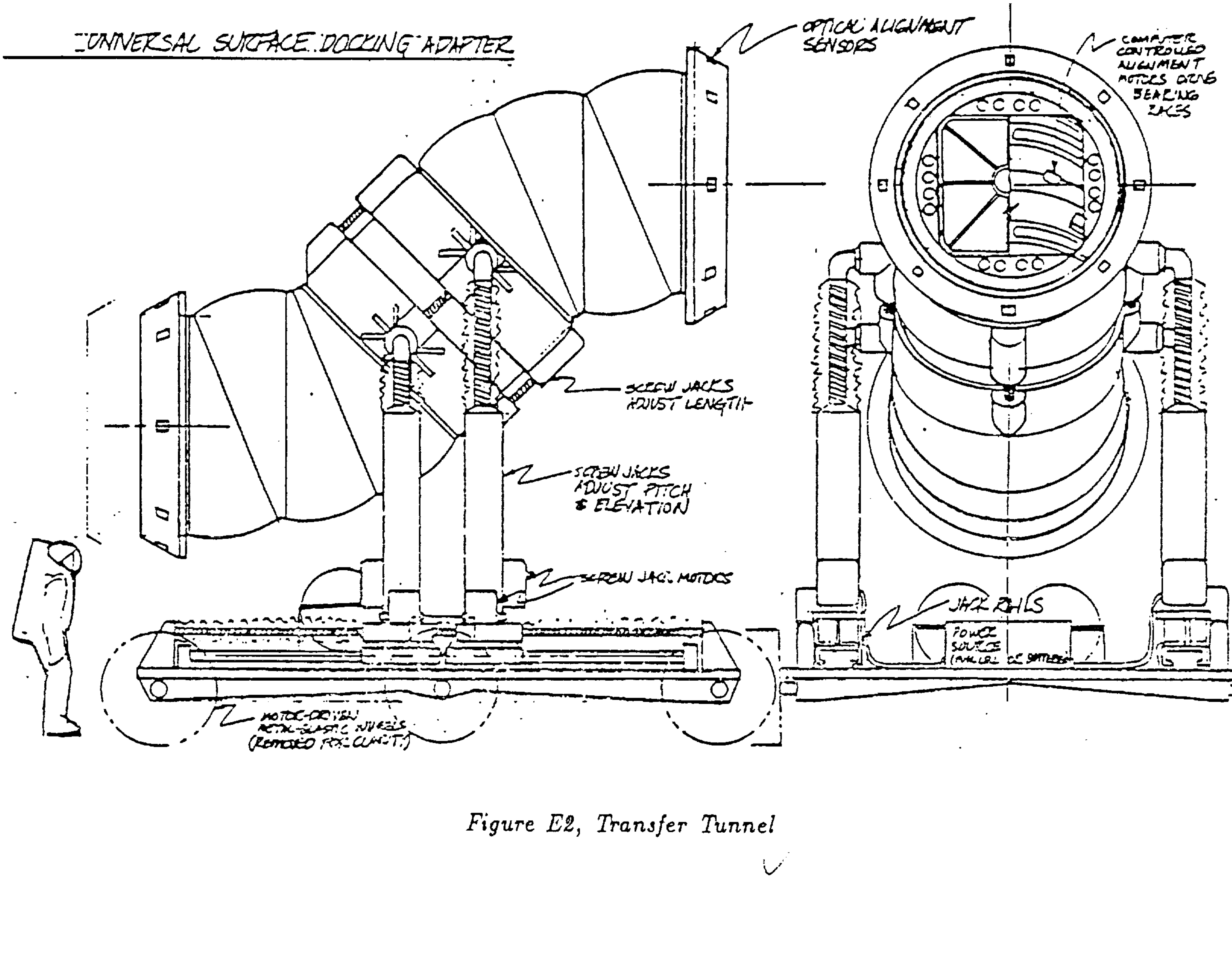

Figure E2, Transfer Tunnel

APPENDIX BB

EVA Life Support System

Group B:
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FAMU/FSU College of Engineering

Purpose: To redesign and expand the current EMU life support system

Date: Saturday, April 21, 1990

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EVA LIFE SUPPORT SYSTEM

Abstract:

The purpose of this project is to redesign the current Extra Vehicular Activity (EVA) suit, also known as the Extra Mobility Unit (EMU), to increase its operating time, safety, and efficiency. Also desired is to design a separate life support system (LSS) to be permanently attached to the lunar Articulating Rover Transportation System (ARTS). The two systems are to be able to interact through the use of an umbilical cord connection. This will allow the crew members to travel long distances without fear of running low on consumables during an EVA.

1.0 Introduction:

It is desired to increase the current EVA operating time, safety, and efficiency without sacrificing the flexibility and geometrical dimensionality of the current EMU.

The basic design decided upon to meet this goal has three distinct parts: the redesign of the current EMU life support system, the adaptation of an EMU oxygen rebreather and cooling system so that it may be permanently affixed to the lunar ARTS, and the interfacing of the above two systems to work in concert. This new extended life support system will allow the crew member maximum flexibility and maximum safety while performing any extended EVA. For a typical EVA that requires traveling a large distance from the home base, the basic benefits are: the crew member does not have to expend the EMU's consumables while riding in the lunar ARTS to and from a destination, and decreased possibility of system failure causing a fatality.

The new EMU design is basically just an technological update of the current design's computer system, oxygen delivery system, and cooling system. New features are the use of cryogenically stored oxygen, and the ability to operate off of an external LSS, outside of a pressurized compartment. Also included is the availability of liquid refreshment during an EVA, and waste management.

The specific problems found with, and corrective changes to, the EMU are discussed in detail in the following sections.

2.0 EVA Suit Problems and Proposed Solutions

The problems of the EVA suit have been mentioned briefly above and some of these problems can be considered major flaws of design, while others are mere inconveniences to the user. However, as EVA activities increase in duration and frequency in the future, the likelihood of a fatality occurring also increases. To reduce the risk of such an occurrence, the solutions to these problems will be discussed.

2.1 Redundancy

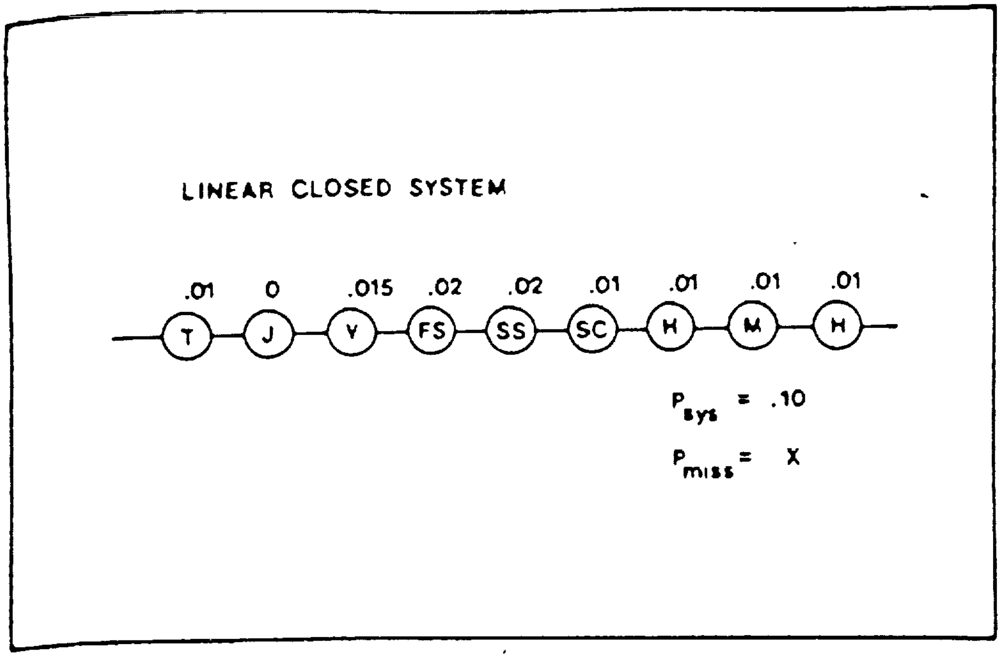


Figure 1. LINEAR CLOSED-LOOP SYSTEM ARCHITECTURE

- T Tank (O-Ring Seal)
- IE Isolation Element
- I Instrument (gage etc)
- J Hard-lined Junction
- V Manual Valve
- VM Manual Bypass Valve
- VS Servo Valve
- VA Auto Add Valve
- SC Scrubber Stack
- H Flex Breathing Hose
- M Mouthpiece (rebreather)
- FS First Stage Regulator
- S Second Stage Regulator

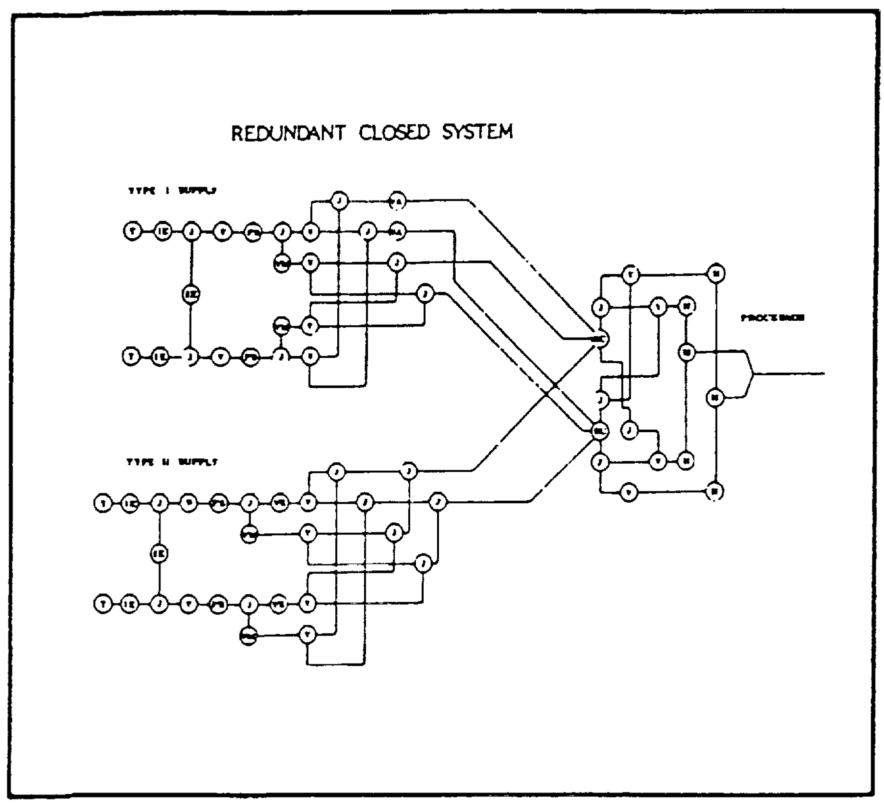


Figure 2. BI-LINEAR CROSS-CONNECT CLOSED-LOOP ARCHITECTURE

The safety of the crew member using the EVA suit is the primary concern of the life support system. Thus, any failure of the suit's systems, short of total destruction, should not result in a life threatening situation. There are quite a few such conditions under which the current EVA suit will fail due to inherent deficiencies in the linear architecture employed, (see fig. 1). The current suit has what is known as in-line redundancy. For example, if a regulator valve for a high pressure oxygen line fails open, a restriction orifice upstream of the regulator will keep over pressurization from occurring in any downstream components. However, if the regulator valve develops a leak there is nothing to keep all the oxygen from escaping to space.

To correct this deficiency, the current system will be modified to conform to the doubly redundant Bi-Linear Cross-Connect architecture developed for cave diving [2], (see fig. 2). Though this system is more complex, with the use of improved technology and materials it could be incorporated into the existing system without any overall geometry change. This system can be shown to be at least fourteen times less likely to have a failure that would cause a fatality.

The current life support system has a very crude emergency system built in to it. The design is such that if the suit pressure should fall below 3.9 psia, then it will switch on in an attempt to maintain the pressure at the proper level of 4.1 psia. Should the cooling system fail, the emergency system can be turned on to provided the necessary cooling and defogging of the helmet visor. This emergency system can be completely removed from the system if the cross-connect architecture is used. In the case of the failure of any component, there is always a second component that can be switched into the circuit before any life threatening conditions develop.

Due to its increased complexity it is necessary to have a computer monitor and control the systems functions. The full role of the computer will be discussed in the next section.

2.2 Embedded Computer Controller

At the heart of the current EVA life support system there is an embedded microcomputer. Though it was advanced at the time, this equipment has become outdated in the

rapidly advancing field of micro electronics. With the incorporation of up to date technology in the life support system, many advantages can be realized, and many difficulties can be overcome.

The current computer requires about one hundred times the power required to run a faster, more advanced computer made with CMOS components and very large scale integration, VLSI, processes. However, the newer computer would have more capabilities than the current one, i.e. about ten times the memory, and speed.

With these increased capabilities, it is possible to perform many more functions than currently possible. For example, the current system has only one diagnostic program which is used to check for a pressure leak. This program takes up to one minute to complete its procedure. With the new processor this diagnostic procedure could be performed concurrently with all other normal operations, with a negligible speed degradation.

Inherent to the control system are its sources of information, the sensors. If the sensors are supplying bad information, then it is almost impossible for the computer to make the correct decisions. As technology advances the size and power requirements of electronic parts decreases. Thus, the suit can be made even more energy efficient by updating its sensors. To insure that the computer is getting the most accurate information, it will be necessary to use two sensors at each monitoring position.

2.3 Consumables Monitoring

One major problem with the current system is the method of determining how much of the system's consumables are actually left, or the rates of usage of said consumables[1]. Basically, the pressure in the oxygen supply tank, the voltage of the battery, and the sublimation water pressure are measured and used to calculate the remaining EVA time, based on a nominal, predefined usage rate for each. With more accurate sensors it would be possible to calculate the actual usage rates and warn of any impending shortfall.

One more accurate method allows calculation of heat generation, by the body, in advance of its actual removal by the cooling system. It uses a sensor to monitor the partial pressure of the oxygen exhaled, which is directly proportional to the heat generated, to

prepare for future heat removal needs, to maintain a constant suit temperature. (see Appendix B)

2.4 Time Limitations

There are four basic time limiting factors in determining the maximum EVA duration, and they are: power, sublimation water for cooling, oxygen volume, and nourishment and relief for the astronaut. Each will be dealt with below, respectively.

The power limitation is due to the finite limit of the EMU's battery. It currently has a total power output of 24.5 Amp hours (minimum), which would only be used when the EMU is not connected to the remote LSS. An exception to this is if the power source of the remote LSS was some how interrupted while the EMU was connected.

The cooling system of the EMU is based on the sublimation process in which a closed loop water circulation system removes the excess heat from the suit and dumps it as it passes through a heat exchanger. The sublimation water is dripped onto the heat exchanger side that is exposed to the vacuum of space, where it freezes and the sublimate to space as steam, taking the excess heat with it. While connected to the remote system this sublimation water would not be used since the cooling water would be pumped through the umbilical to the lunar ARTS where it would pass through a radiation heat exchanger.

Since cryogenic oxygen is to be used in place of the pressurized oxygen, more oxygen can be stored in a smaller volume. With the currently in use standard size tank, the time limit for oxygen is pushed to almost 3 days at an optimum usage rate. Under the most strenuous conditions this time is still almost 24 hours. An added benefit of this adjustment is that the heating of the oxygen can be accomplished by tying a line from the body cooling system to the oxygen. Thus, the excess heat is used to heat the oxygen to a tolerable temperature (see Appendix C).

The nourishment mentioned above is a vitamin enriched water that is available to the astronaut through a sip-stick located in the EMU's helmet. This refreshment is available at an astonishing flow rate of 240 cc per hour. An eight hour supply is stored in the EMU back pack and an additional 16 hours supply is located in the remote LSS.

The waste management system allows for 1000 cc storage of urine for both men and women, and menses for women. A provision will be made so that this liquid can, in an emergency, be used by the sublimation system to maintain cooling capacity of the system, should the sublimation water be exhausted. Due to complexities fecal matter will not be stored. However, a mild constapative can be added to the drinking water of a suit to help control the problem.

2.5 Size Limitations

Most of the current EMUs are designed either for one specific person, or at best the people with the same size body frame, thus most likely the same physiological burn rates of consumables. The new system is self regulated and hence can automatically match the physiological requirements of any human. However, the computer can not as yet control the physical size of the EMU, so an adaptable size suit has incorporated as an extra feature of this design.

3.0 Description of Major Components

3.1 Cryogenic O_2 Tanks

Stores primary O_2 used for breathing. Flow is controlled by onboard computer. The tank has maximum operating pressure of 20.68 MPa at 91 K. Tank has ID of 13.0 cm, capacity of 0.0178 m^3 and stores 2.0 kg of oxygen. With such low storage temperature, the oxygen must be heated for human consumption. The dimensions of the tank conforms to that of the fuel cell O_2 tanks for uniformity.

3.2 Rebreather

The rebreather(RB) system used is a miniaturization of the fully redundant architecture implemented by Cis-Lunar Development Laboratories in their experimental cave-diving scuba gear setup [2], (see fig. 2).

Because the current EMU system is a so called "linear" system, its safety is compromised. Many of its components are critical, such that if any one of these fails, death is imminent, unless a safe-harbor is reached quickly.

Because the RB is fully redundant, the possibility of a system-wide failure can be shown to be fourteen times less than the current EMU system.

3.3 Umbilical Chord

It serves as an LSS interface between the astronaut's EMU and the external LSS mounted on the lunar ARTS. The umbilical allows full or partial life support from a remote LSS, i.e. if only oxygen is needed, then only oxygen has to be supplied. The connections on the ends of the umbilical are equipped with a fail-safe design for unexpected disconnection while in operation. That is, if the umbilical is disconnected the system will go into a standby state and not malfunction, thus keeping the loss of system consumables to a minimum.

3.4 Pumps

There are two pumps needed for the external LSS to be integrated along with the back pack. One is a pump to circulate the air from the suit through the umbilical to the

external LSS and back again. The other is to circulate the water in the body garment when the external LSS is operating and the back pack's pump is turned off.

3.5 Computer Control Systems

Due to the complexity of the RB apparatus it is necessary to have a computer system in control of its operations. Knowing this many aspects have been considered such as module size, power requirements, and sensor communications.

Using a miniaturization technique called very large scale integration (VLSI) it is possible to put an entire computer on one silicon chip. Many such generalized chips are readily available on today's market. In the interest of development speed, only currently available technology will be used in the RB's control system.

Getting down to specifics: it has been determined that a complete computer module will fit into a five cm cube. The guts of the computer module will be a military spec. CMOS 8051 based microprocessor with a memory complement of 64 kilobytes of RAM and 64 kilobytes of ROM. The main communications bus will resemble a local area networking scheme.

An important part of the computer system is the interaction of all of its components. That is, each of the three computer modules in the system can communicate with each other, and all of the sensors in the system. In this way the control system is made redundant and self regulating.

A key to the system's successful operation is its democratic process for making decisions and taking actions: majority rules. Each of the computers can take data from the sensors individually, but no action can be taken unless at least two of the modules arrive at similar decisions. In some cases it be necessary to silence the opposition by forcing it to either reset itself or shut down. This system has been and is being successfully used by the U.S. Space Shuttle fleet.

To deal with the many different kinds of data to be collected many different kinds of sensors are necessary. Some of the basic types are: resistive, photoelectric, thermal, electrochemical, and magnetic.

In all cases where sensors are used there will be at least two sensors reading the same

data. This double redundancy is a minimum requirement to insure the safety of the system.

The biggest problem with such extensive logic is the temperature variance of the system. Almost an industry standard, is the fact that most electronic devices do not operate below $-25°C$. This is also the case for most sensors, with the exception of temperature sensors. Because of this, some sort of heating system is necessary to allow successful operation.

One other minor problem is the necessity of similarly outfitting the EMU with a computer control system. This is required so that the RB can make use of the EMU's service, such as preheating the oxygen to tolerable levels.

Though some new problems present themselves in this evolution of life- support, many problems are solved. However, as a final safety precaution, should there come about a total computer controller failure, the system will revert to a totally manual fail-safe condition. In this condition the EMU will operate as a totally mechanical unit.

4.0 Rebreather Design Alternatives

Alternate designs are considered prior to finding an optimum design. Some alternatives are preferred over others due to their attractive options. One consideration for the RB is to place the cryogenic oxygen tanks inside the existing back pack without the use of an auxiliary system. This option would of course increase the oxygen content and the EVA time, but would also require an increase in power used to heat the cryogenic for human consumption. Another alternative is to decrease the RB overall size such that it can be carried on the suit in addition to the back pack. However, the increase in weight and because the added unit could reduce the mobility of the astronaut and thus proves infeasible. Since the aim is to increase EMU time and efficiency of operation, the final alternative is to have an auxiliary RB that can be used by more than one astronaut for long trips on the lunar surface. The astronauts would be able to use the same RB via multiple umbilical chords. All the alternatives would utilize existing components already on the back pack (see Figure 3).

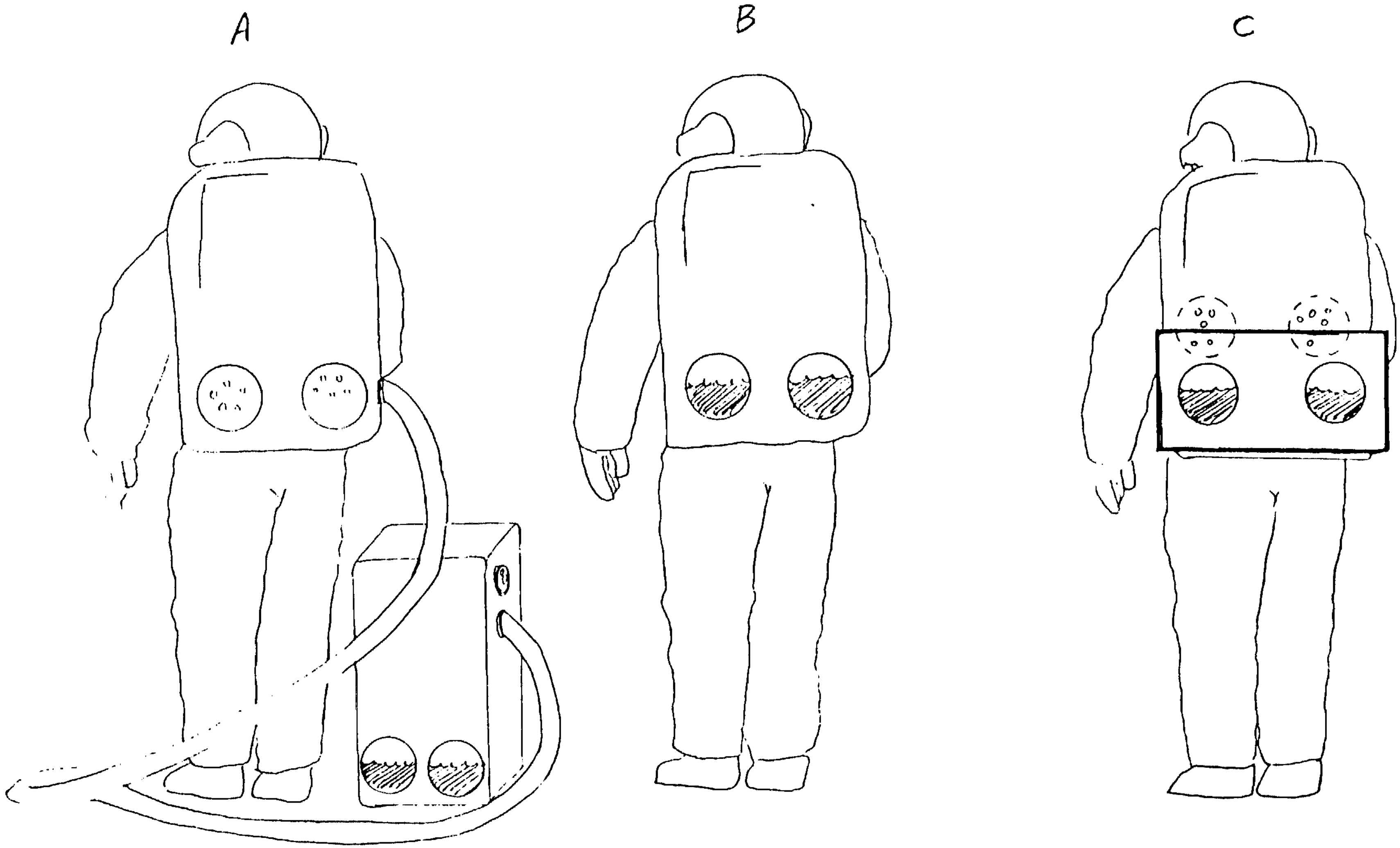


Figure 3. DESIGN ALTERNATIVES FOR LIFE SUPPORT

5.0 Future Applications

The RB system is designed to work with the lunar ARTS. Future applications will allow the system to operate with suits having higher internal pressure such as the hard suits now in the developmental stages. With an increase in cryogenic storage capacity, multiple umbilical may be used, and will also increase even more operating time.

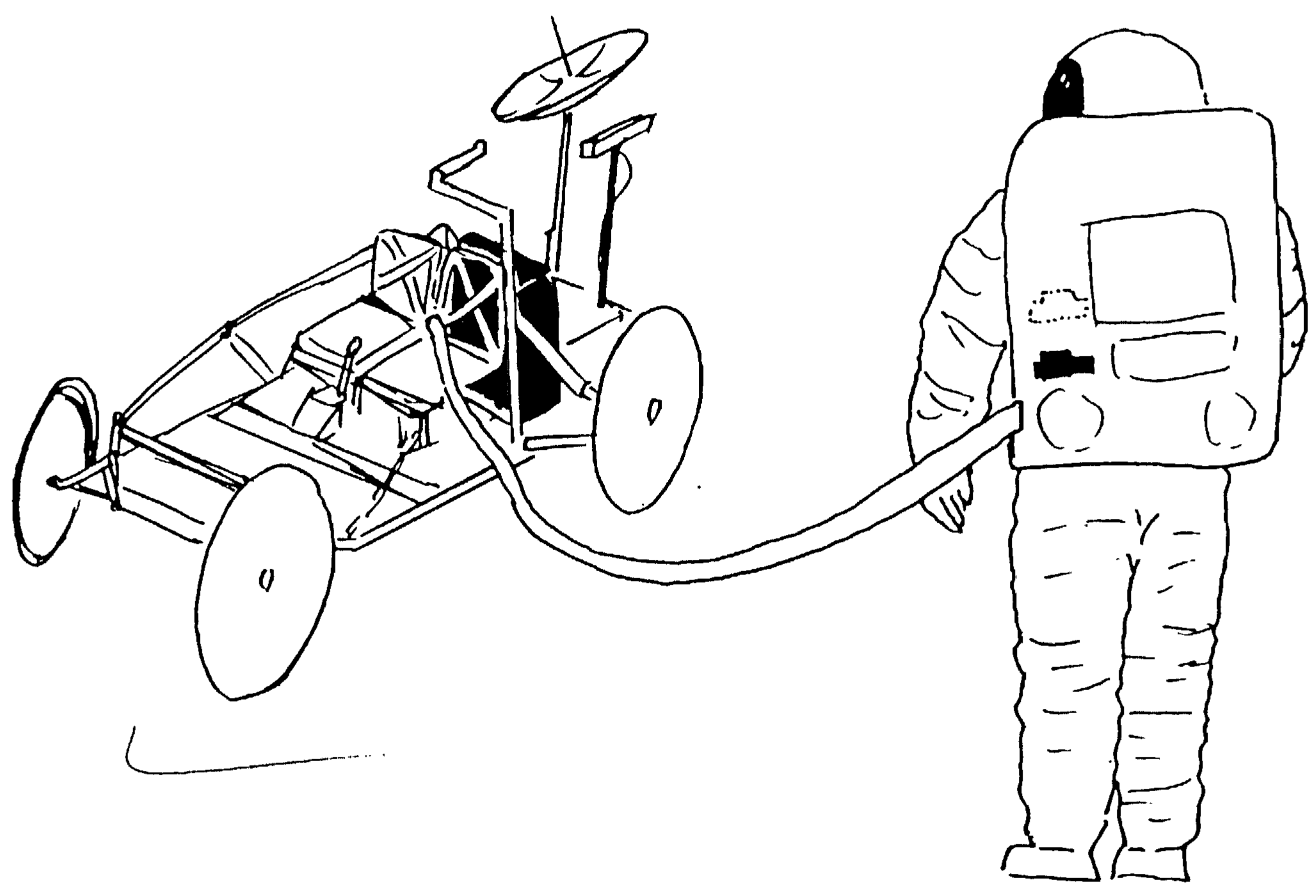


Figure 4. CONCEPTUAL DESIGN OF AUXILLIARY REBREATHER

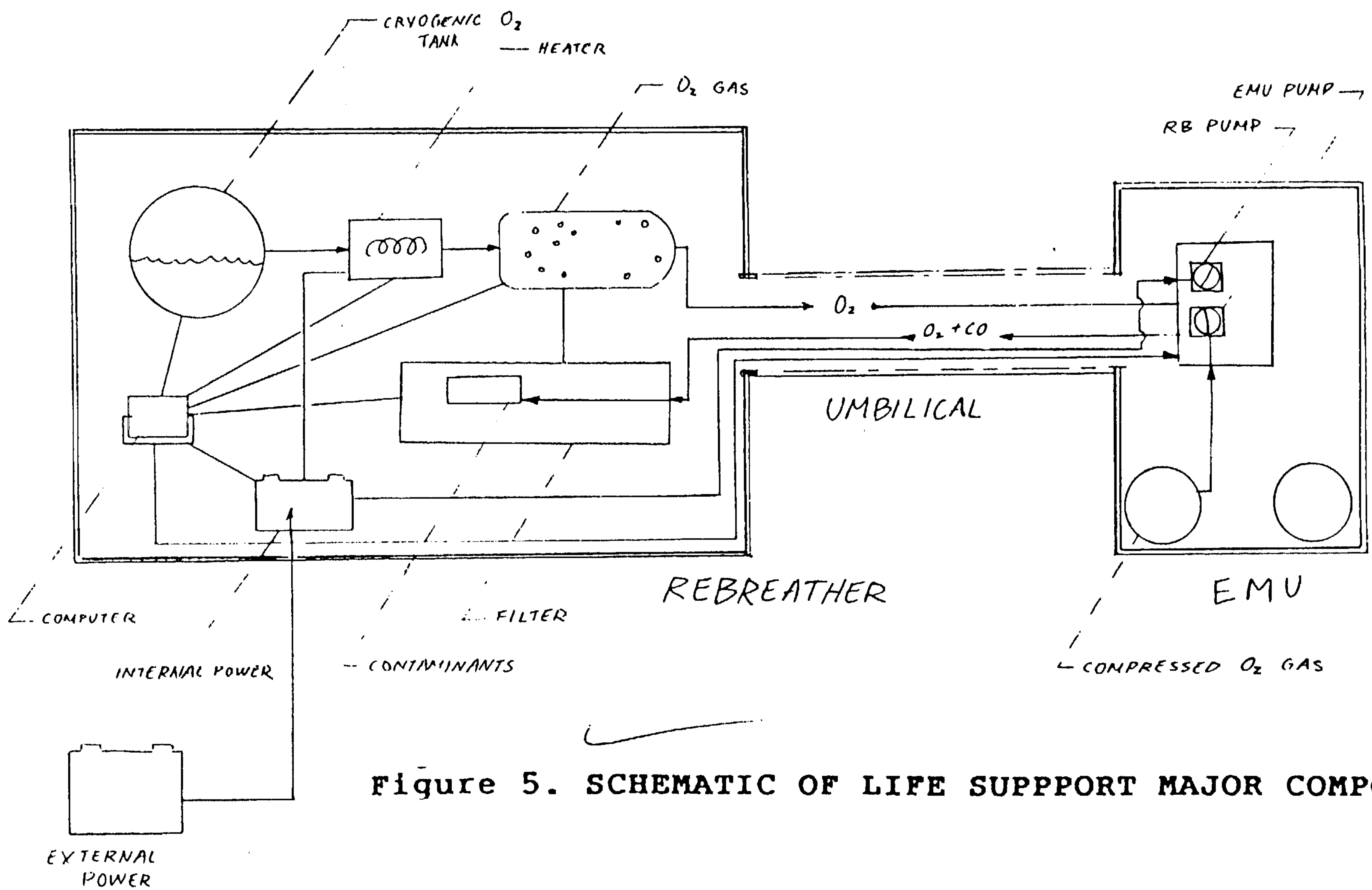


Figure 5. SCHEMATIC OF LIFE SUPPPORT MAJOR COMPONENTS

References

1. NASA, *EMU Systems 2102 Training Manual*, Pub# JSC-19450 Dec. 1, 1984
2. U.S. Deep Caving Team, *The Wakulla Springs Project*, 1989
3. NASA, *Atmosphere Design Considerations*, Pub# NASA-STD-3000

Weighted Property Index Chart for selecting Rebreather Type

		(1)(2)	(1)(3)	(1)(4)	(1)(5)	(2)(3)	(2)(4)	(2)(5)	(3)(4)	(3)(5)	(4)(5)	Wt. factor Wi
1.	Mobility	0	1	0	0							0.1
2.	Multiply Capability	1				0	0	1				0.2
3.	Weight		0			1			0	0		0.1
4.	Capacity			1			1		1		0	0.3
5.	Power consumption				1			0		1	1	0.3

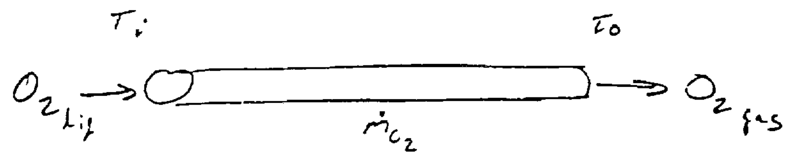
	0.1 Mobility	0.2 Multiple Capab.	0.1 Weight	0.3 Capacity	0.3 Power cons.	TOTAL
Design A	2 / 20% / 0.4	10 / 100% / 10	10 / 100% / 0.1	5 / 50% / 2.5	1 / 100% / 1	4.09 → selection
Design B	10 / 100% / 10	0 / 0 / 0	1 / 11% / .01	10 / 100% / 10	0.1 / 10% / 0.01	4.01
Design C	8 / 80% / 6.4	5 / 50% / 2.5	1 / 10% / .01	5 / 50% / 2.5	0.2 / 10% / 0.04	2.62

APPENDIX A. WEIGHTED PROPERTY INDEX FOR REBREATHER TYPE

HEAT CALCULATION

The body heat generation calculation can be shown to be greater than the required heat necessary to bring the liquid O_2 is at an ideal breathing temperature.

$T_i = 100\ K$
$T_o = 295.75\ K$
$C_P = 0.92\ kJ/kg\,K$



Nominal heat rate = 292.87 W

Maximum mass flow rate of O_2 = 2.5 g/hr (EMU systems 2102 Training Man 2.2-2)
$\dot{m} = 6.6 \times 10^{-4}$

$$q_{max} = \dot{m}\, C_p\, \Delta T = 6.6 \times 10^{-4} (920)(295.75 - 100) = 119.6\ W$$

Nominal heat rate > q_{max}
292.77 W > 119.6 W

DRINKING WATER STORAGE VOLUME

It is desired to know the amount of water needed for a crew member during a 24 hour period.

$\dot{m}_{H_2O} = 240\ cm^3/hr\ (24\ hr) = 5760\ cm^3 \rightarrow 17.9\ cm/side$ of cub
(NASA, EVA Physiological Design Requirements, Pub# NASA-STD-3000. 14.2-5)

NASA TECH BRIEF

NASA Tech Briefs are issued to summarize specific innovations derived from the U.S. space program, to encourage their commercial application. Copies are available to the public at 15 cents each from the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

Rate of Heat Extraction Controller for Environmental Control

The problem:

To regulate the temperature automatically within a watercooled environmental control suit.

The solution:

An automatic control device measures a physiological parameter related to heat production and conditions it to control the heat removal capacity of the suit.

How it's done:

A metabolic rate monitor uses a polarographic cell to measure the partial pressure of oxygen in exhaled gas, and generates a signal proportional to the amount of oxygen consumed.

The oxygen consumption rate is directly related to the heat production rate of the worker enclosed in the suit. Hence, this signal is used to control the efficiency of a thermoelectric cooling system. Changes in the temperature of the water input to the suit cooling coil produce changes in its heat removal capability and maintain a constant temperature within the suit.

This device should find application in the areas of thermal control and life support systems.

Note:

Documentation is available from:
Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151
Reference: TSP-69-10516

Source: Paul Webb, James F. Annis, and Samuel J. Troutman of Webb Associates
Yellow Springs, Ohio
under contract to
NASA Headquarters
(HQN-10318)

Category 01

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APPENDIX C. NASA TECH BRIEF: ENVIROMENTAL CONTROL

NASA Tech Brief

National Aeronautics and Space Administration

May 87 B87-10236/ARC-11616

Hard Suit With Adjustable Torso Length

Torso sizing rings allow a single suit to fit a variety of people.

Ames Research Center, Moffett Field, California

A hard space or diving suit has an adjustable-length torso that will fit a large variety of wearers. Conventionally, each suit has been customized to the individual's torso length, but this process has been expensive, particularly when spare suits had to be made. The new adjustable-size concept with its cost-saving feature could be applied to other suits that are not entirely constructed of "hard" materials, such as chemical defense suits and suits for industrial-hazard cleanup.

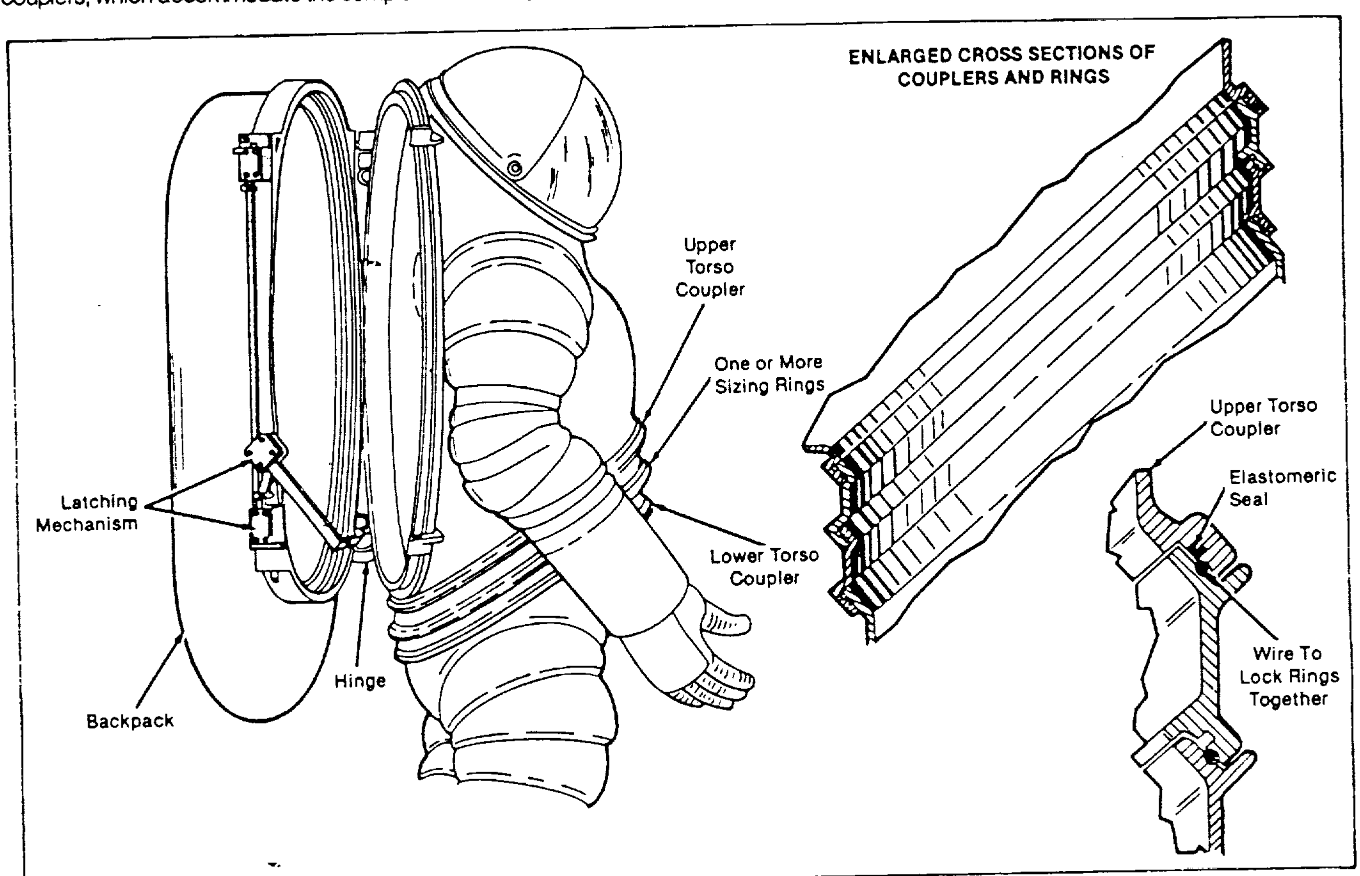
In the adjustable-torso-length suit (see figure), sizing rings are inserted between the upper and lower torso sections to increase the torso length. When no rings are required, the coupler of the upper torso covering fits over the corresponding coupler of the lower torso-covering section.

The sizing rings have upper and lower couplers, which accommodate the complementary couplers of the torso sections or of other rings. Elastomeric padding between the rings and couplers forms a pressure-aided hermetic seal. Two facing surfaces of each mating pair contain matching grooves, into which a flexible cable or wire may be inserted to hold the parts assembled.

The back of the adjustable torso is formed with a large opening, which is closed off by the backpack containing life-support, communication, and other equipment. This opening covers almost the entire back of the upper torso-covering section and is used for entry and exit. The coupler of the upper torso section is located immediately beneath the opening and slants up and forward — as consequently do all of the rings and the coupler of the lower torso section. This arrangement allows ample back opening for entry and exit of the largest wearer.

This work was done by Hubert C. Vykukal of **Ames Research Center.**

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning rights for the commercial use of this invention should be addressed to the Patent Counsel, Ames Research Center, Mail Code 200-11A
Moffett Field, CA 94035



Sizing Rings are inserted between the coupling rings of the torso portion of the hard suit. The number of rings is chosen to fit the torso length of the suit to that of the wearer. The sizing rings mate with, and seal to, the coupling rings and to each other.

APPENDIX D. NASA TECH BRIEF: HARD SUIT

For additional information contact the following office: Manager, Technology Utilization Office, NASA STI Facility, P.O. Box 8757, BWI Airport, MD 21240.

Appendix E

***** SPECIFICATIONS *****

NO.	E/O	REQUIREMENTS
		* GEOMETRY
1	O-MAJ	REBREATHER BOX: 0.3048 X 0.3048 X 0.9144 m
2	E	OXYGEN TANK: ID = 0.1296 m, OD = 0.1236 m
3	E	UMBILICAL CHORD: OD = 5 cm, LENGTH = 2.5 m
		* FORCES
4	E	SUIT PRESSURE = 27.58 KPa (4.0 psi)
5	E	NORMOXIC OXYGEN: => 22.34 KPa (3.62 psi)
6	E	CO2 PARTIAL PRESSURE EXPOSURE = 1.03 KPa (0.15 psi)
7	E	RATE OF PRESSURE CHANGE < 0.34 KPa/sec (0.05 psi/sec)
		* OPERATION CONDITIONS
8	E	TEMPERATURE OF AIR BREATHED: 291.5 - 299.9 K
9	E	OXYGEN CONSUMPTION RATE: 0.15 - 2.5 g/hr
10	O-MAJ	OXYGEN (CRYOGENIC) CAPACITY: MASS = 2.0 Kg
11	O-MAJ	WATER CAPACITY: 5760 cc/24 hr period
12	E	THERE MUST BE SUFFICIENT TOTAL PRESSURE TO PREVENT THE VAPORIZATION OF BODY FLUIDS.
13	E	OXYGEN PARTIAL PRESSURE MUST NOT BE SO GREAT AS TO INDUCE
14	E	ALL OTHER ATMOSPHERIC CONSTITUENTS MUST BE PHYSIOLOGICALLY INERT OR OF LOW ENOUGH CONCENTRATION TO PRECLUDE TOXIC EFFECTS.
15	E	BREATHING ATMOSPHERE COMPOSITION SHOULD HAVE MINIMAL FLAME/ EXPLOSIVE HAZARD.
		* FOOD AND DRINKING WATER DESIGN REQUIREMENTS
16	E	WATER: SHALL BE AVAILABLE DURING EVA AT A RATE 240 cc/hr FOR EVA OVER 3 HOURS
17	E	EVAs OF 4 HRS OR LESS IN OPERATION MAY BE MANAGED WITH 200 Kcal (795 BTU) OF FOOD.
18	E	EVAs OF GREATER THAN 4 HRS IN DURATION AT LEAST 48 HRS APART MAY BE MANAGED WITH 750 Kcal (2975 BTU) OF FOOD.
19	E	MATERIALS USED SHALL MEET THE CURRENT FDA REQUIREMENTS THAT PERTAIN TO FOOD AND DRINKING WATER.
		* BODY WASTE MANAGEMENT
20	0-MAJ	BODY WASTES TO BE ACCOMODATED: ACCOMODATION OF 1000 cc (33 oz) OF URINE FOR MEN AND WOMEN, AND MENSES FOR WOMEN.
21	E	CONTAMINATION PROTECTION: PREVENTION OF ODOR, PARTICLES, BIOTICS CONTAMINANTS, AND/OR TOXICANTS.
22	O-MAJ	DURATION ACCOMODATION: ACCOMODATION OF BODY WASTES FOR MAXIMUM SUITED DURATION.
23	E	ORAL/NASAL BREATHING ENVIROMENT: PROTECTION FROM INSUIT DEFECATION, VOMITTING, LOOSE FOOD OR WATER PARTICLES, AND FREE-FLOATING FLUIDS.
		* SAFETY
24	O-MAJ	DOUBLE REDUNDANCY IN RB WHEREVER POSIBLE
25	O-MAJ	DEFAULT SETTINGS FOR ELECTRICAL FAILURE
26	E	SUIT RUPTURE PROTECTION
		* MATERIALS
27	O-MAJ	FIRE SAFE MATERIALS
		* CONTROLS

28	E	COMMUNICATIONS, CAUTION, AND WARNING: CAPABILITY FOR REAL-TIME DOWNLINK, AS WELL AS IN-SUIT CAUTION AND WARNING ALARMS, PROVISION OF CAUTION AND WARNING ALARMS FOR INTERVEHICULAR CREWMEMBER SUPPORT.
29	O-MAJ	MOBILITY: MINIMAL INTERFERENCE WITH PERSONEL MOBILITY.
30	E	MONITOR PHYSIOLOGICAL SIGNS: HEARTBEAT, BLOOD PRESSURE, BODY TEMPERATURE
31	E	MONITOR CO2 LEVEL
32	E	CONTROL OXYGEN PURIFICATION (SCRUBBING SYSTEM)
33	E	CONTROL OXYGEN DELIVERY SYSTEM
34	O-MAJ	CONTROL COMMUNICATIONS WITH LUNAR ARTS WHEN IN OPERATION
35	E	CONTINUOUS DIAGNOSTICS ON ELECTRICAL SYSTEMS, CONTINUOUS DIAGNOSTICS ON SENSORS (i.e. CONNECTORS TO ARTS OXYGEN LINKUP)
36	E	DOUBLE REDUDANCY OF SENSORS AND EMBEDED CONTROLLERS
37	E	FAULT REDUNDANCY: IF TOTAL ELECTRONIC FAILURE OCCURS SYSTEM WILL CONTINUE OPERATION ON DEFAULT SETTINGS
38	E	ENTIRE ELECTRONIC SYSTEM NEEDS TO BE GROUND FAULT PROTECTED SUC THAT ELECTRICAL SHORT-OUTS WILL NOT CAUSE CONTROLLERS TO FAIL OR HALT.
39	E	ELECTRONIC SHIELDING: FOR EMBEDED SYSTEM INCASE IN LORENTZ AND FARADAY CASES.

APPENDIX CC

90

PRESSURIZED LUNAR ROVER VEHICLE FOR GREATER DISTANCES

EML - 3541 Introduction to Design
Dr. Chandra

USRA DESIGN PROJECT

Group: Richard Leach, Linda Watley, and Michelle Clemens
April 21, 1990

Special contributions (Morea S.F., Reference 9)

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* Weighted Property Index

ABSTRACT

gram. sentence construction

The goal of this project is to design a ground based vehicle which will travel for longer distances than a 37.5 kilometer radius from base on the lunar surface. The existing design is limited to this 37.5 kilometers radius because EVA suits which the astronauts wear have limited life support contained in them. Designing a pressurized vehicle would eliminate the need for these EVA suits during travel, therefore would solve the problem of the restricted traveling distance. In addition, the conceptual design will encompass the following: a manned, 3 day mission, a traveling radius of 150 km (10 - 15 km/hr) and lunar surface evaluation capabilities (through crew experiments, photography and computer analysis). The primary design considerations are structural, power, and controls components. The present design of the pressurized vehicle (10-14 psi) is a cylindrical double hull vessel with semi-circular ends which include man-locks and the necessary living facilities. The optimum power source for locomotion is the Isotope Brayton Cycle which implements the transportation of thermal energy into shaft work by the turbines. The fuel is either Pu-238, Po-210, or Cm-244. The control system and navigation use previous implemented equipment such as the gyrocompass, odometer, thermocouples, and transducers, although the steering of the vehicle will be controlled through the variable wheel rotation ratios. This conceptual design will then have the capability to be adapted to a wide variety of other missions.

1.0 INTRODUCTION

v. poor sent.

In order for human understanding of the universe to continue to expand, sp it is necessary that exploration for what of the solar system proceeds. The moon, which is the closest body in thee solar system is a logical first step. Exploration of the lunar surface will be greatly facilitated by the development of an extended range lunar roving vehicle. The purpose of this project is to design such a vehicle which can travel distances greater than 37.5 kilometers from base and be utilized in a wide range of missions.

2.0 DESIGN SPECIFICATION AND ALTERNATIVE DESIGNS

max. or min.

The design specifications or constraints ~~are~~ listed below:

* Travel a minimum distance of 150 kilometers from the base
* Have the ability to stay away from the base for at least 3 days
* Have the capacity to carry four crew members
* Travel a speep of 10-15 km/hr sp
* Gather lunar surface data

See Appendix A for the final detailed specification list. Our alternative table is included in Appendix B. The options are stated and discussed in the following text.

3.0 STRUCTURAL DESIGN

The design consists of a pressurized cabin which will contain the life support for the crew members. It will accommodate up to four people and be designed to travel for a average period of three days. It will have capabilities of traveling an average of 10-15 kilometers per hour in approximately a 120 kilometer radius from the base.

3.1 Geometry

The cabin geometry options are the following: cylindrical with spherical end caps, cylindrical with flat end caps, box shaped, polygon shaped, or elliptical. When considering structural efficiency, a cylindrical shape with spherical ends is the best design. This shape will allow the smallest thickness of the vessel when an interior pressure is maintained. The weighted index for the determination of the the structure design is

given in Appendix C in Table C-1. Taking different factors into consideration it is shown that the cylindrical shape with the spherical end caps results in the best solution. Reviewing previous designs and space needed, dimensions were obtained. The dimensions are: cylinder of length 6 meters with semi-spheres of 3 meter radii. The schematic of the vehicle both inside and out are shown in Figures 1 and 2 on the following pages.

3.2 Material

The structure consists of a double-hull cabin (an inner shell and an outer shell). The outer shell serves as protection, strength, and insulation. Between the two shells insulation is used as a thermal barrier. The conventional material for the inner shell of pressurized vessels is aluminum alloy. The options for the outer shell are the following; stainless steel, carbon/graphite composite, titanium, or aluminum. The cabin will be maintained at a pressure between 10 and 14 psi (38-101 kN/MxM). The option chosen is an aluminum alloy 7075-T6 as an outer shell as well as an inner shell. The weighted index which supports this conclusion is shown in Appendix C at table C-2. Windows need to be incorporated to allow visual abilities of the lunar surface from within the cabin. Windows similar to the space shuttles' will be used. They consist of three separate structural members. The outer member is the thermal window. It is made of fused silica approximately .7 inches thick. This window is mounted in a retainer and then to the outer shell of the vessel. The next part consists of a redundant window (fused silica about 1.4 inches thick) and a pressure window (highly tempered aluminosilicate glass about .7 inches thick). These two are both mounted in a retainer with space between and then to the inner shell of the vessel. A schematic of the window system is shown in Appendix J figure J-1. (1) Windows, however include the problem of the luner dust collecting on them. To avoid this problem the following mechanism will be utilized. A cylindrical case with a very small slit lengthwise will be used. In this casing, a thin transparent film will be stored. This film will be extracted out through the small slit. This slit will not allow luner dust to enter. The film will extend from the casing, over the window, and to another casing. When the film becomes covered with lunar dust, the crew members will be able to electronically roll the film to the second casing. This will cause the casing of the clean film to dispense a clean layer over the windows. These casings will be unattached and cleaned after each mission.

3.3 Lighting

External and internal lighting will be needed. Fluorescent light bulbs will be used for internal lighting. One option for exterior lighting is in the form of earthshine (sunlight reflected from the earth). The moon

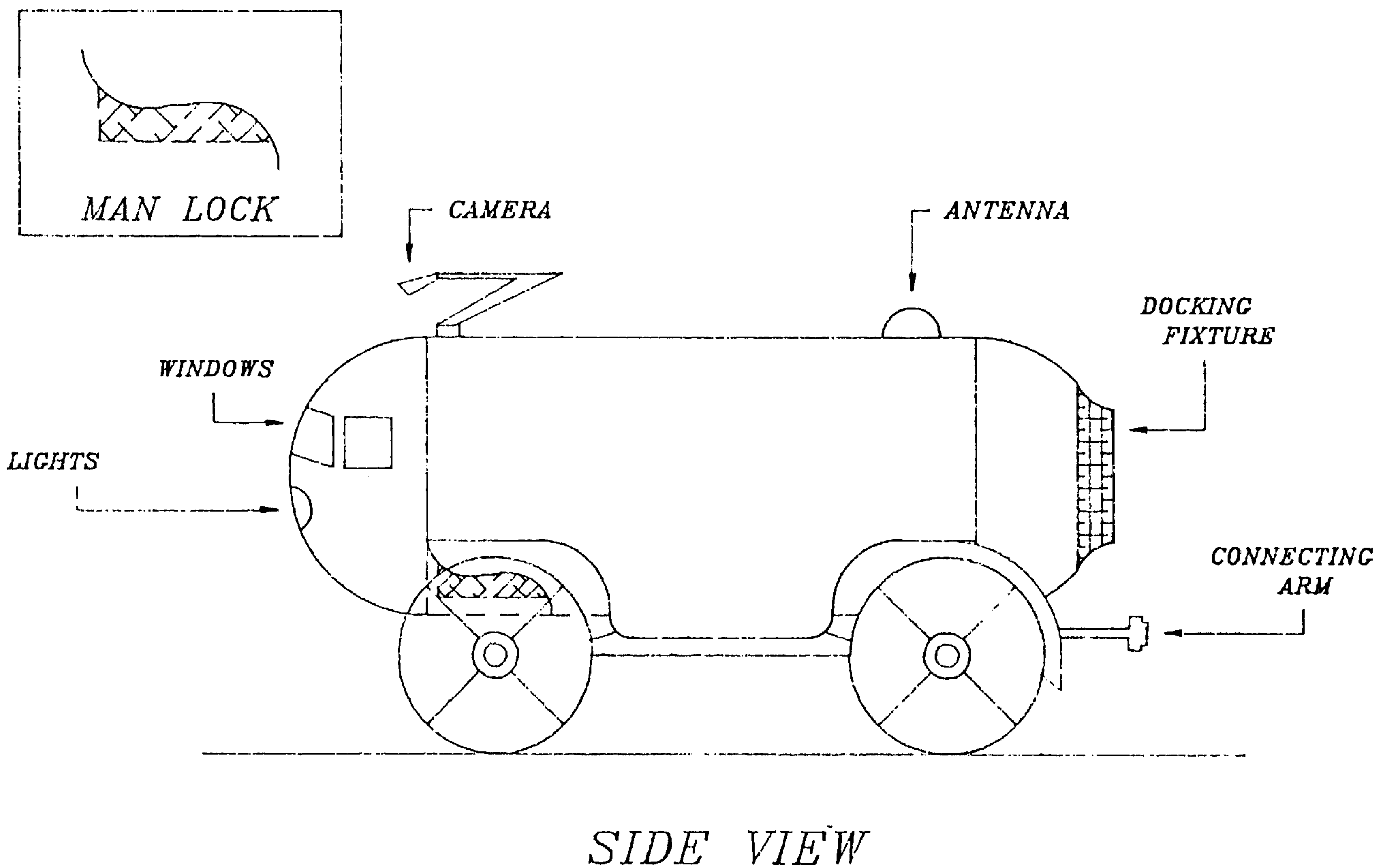

FIGURE 1 - CONCEPTUAL DESIGN OF EXTERIOR PRESSURIZED VEHICLE

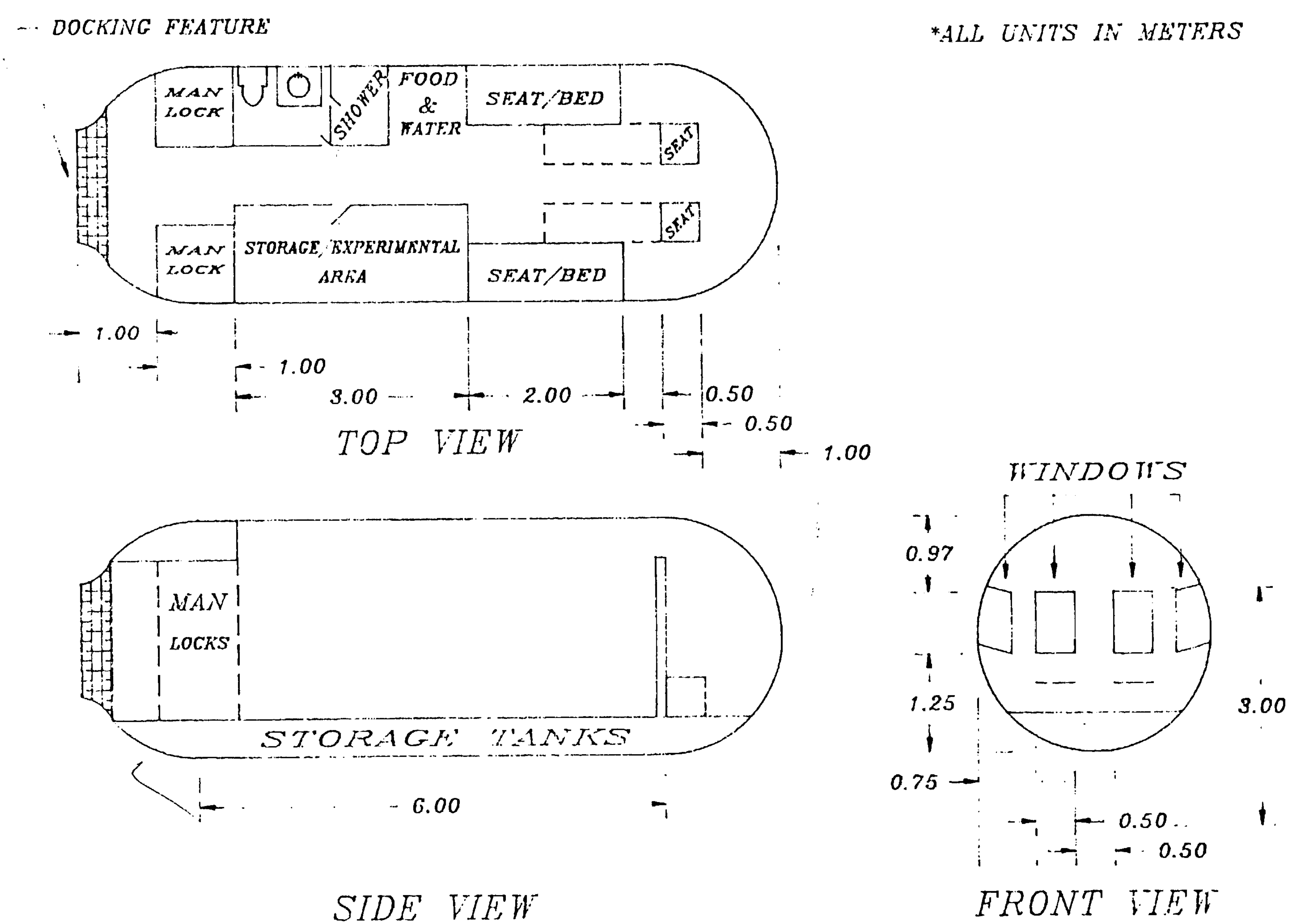

FIGURE 2 - CONCEPTUAL DESIGN OF INTERIOR OF PRESSURIZED

and earth have different radii along with albedo's (fracture of light reflected from a body). This results in earthshine. The brightness of full earthshine is 58 times greater than the brightness of a full moon as seen from earth. This option , however, is not practical because sites on the far side of the moon never receive earthshine. This and other types of natural lighting are inefficient because they are dependant on location. (2) The need for exterior lighting will be fulfilled by floodlights. These floodlights will be encased in the same material that is used in the exterior pane of the window system. These floodlights will be mounted close to the windows so that they will be protected from lunar dust by the same mechanism which protects the windows.

3.4 Airlocks and Docking Fixtures

A docking fixture is an option such that attachment to other structures is possible. The docking fixture will be in the rear of the vehicle. The vehicle will be capable of connecting to the base. At this time the hatch will be opened and there will be direct access from the vehicle to the base and vice versa. Man-locks are another option to give explorer access to the lunar surface directly. For the airlocks, there are a few options. First there is a rear entry EMU/airlock concept. The pressure suits themselves are used as an airlock by developing a closure for a rear entry type hard upper torso that fits a hatch. Then an inner hatch is closed over the entry, the EMU is undocked from the vehicle, and the pressure connection broken. Another option is a man-lock type airlock. This is a small container that conforms to the shape of a single crewman in a EMU. The astronaut climbs into the tightly fitting box by opening the pressurized side. The box is closed and the pressure is relieved. Then the unpressurized side is open and the astronaut exits the vehicle. (3)

4.0 MAIN POWER

In the effort to find a suitable energy source to propel a lunar rover vehicle, a list of system requirements and desirable options was created. The primary requirements for the energy source were as follows:

* Dependable energy flow
* Portability
* Safe operation
* Use of available fuel sources
* Ability to withstand environmental extremes

In addition to these essential features, a number of desirable features were also considered. These include:

* Low weight

* Limited number of moving parts
* Limited amount of fuel needed on missions

To fulfill these essential requirements and satisfy as many of the desired options as possible, a number of power system options were considered. Several of these were immediately found to be unacceptable either due to operational difficulties or impractical physical requirements. While sorting through these various power systems, three stood out as having an acceptable combination of features usable in the lunar roving vehicle. Among the desirable features of these systems, each used heating and cooling cycles which could be employed to provide temperature control for equipment and environmental systems.

4.1 Hydrogen-oxygen combustion engine

The hydrogen-oxygen combustion engine is a multiple cylinder,reciprocating engine using pressurized oxygen and hydrogen as fuel (see appendix F). The exhaust water vapor is then routed to a heat exchanger where it is condensed. The water condensate is then piped into a holding tank for later purification. Several identical power units may be used in parallel to maintain the necessary power output.

Among the major advantages of this system:

1) Fuel elements are required materials at the lunar base and thus are readily available
2) High energy output (3 kw per unit)

The disadvantages include:

1) High weight (over 9,000 lbs) requiring multiple trailers
2) Waste water is contaminated by oil
3) Engine components must be protected from lunar environment
4) Necessary fast operating oxygen injectors not yet developed
5) large amounts of fuel and waste water must be transported about

4.2 Isotope Brayton cycle

The closed loop Brayton power cycle consists of four separate loop systems. The argon gas loop is the workhorse of the system, gathering and transporting thermal energy to be converted into shaft work by the turbines. The sodium-potassium loop is used to transport thermal energy from the isotope fuel to the argon loop. The freon loop transfers waste heat from the argon loop to a radiator panel, and a propylene glycol loop used to maintain equipment operating temperatures (see appendix H).

The isotope fuel may be either Pu-238, Po-210, or Cm-244. These isotopes can be packaged into convenient fuel modules which can be shielded to prevent crew exposure to radiation, and configured to eliminate the possibility of combining into a critical mass. For a power system such as this, it is desirable to maintain the rate of energy generation at as constant a level as possible. Because the energy demands of the lunar rover vehicle will vary greatly, the load can be evened out by using excess energy to recharge battery arrays during low load periods. The stored energy can then be discharged to supplement the alternator output during high load periods. These battery arrays can also serve as a source of emergency power in the event of a mechanical failure.

The isotope Brayton cycle closed loop power system offers a number of advantages:

1) Fuel source is small and independent of the base
2) Provides power for extended missions (up to 45 days)
3) Low weight (approx. 3000 lbs requiring only 1 trailer)
4) Low fuel transportation costs
5) High energy output (up to 15 kw)

As is the case with all such systems, there are some disadvantages as well:

1) Nuclear fuel could endanger crew
2) Spent fuel presents disposal problems
3) Large number of mechanical systems which could fail

Of the power systems examined, the isotope Brayton cycle power system seems to offer the greatest number of advantages. This system is able to deliver a continuous high power output for an extended mission of up to 45 days.

4.3 Fuel cells

Fuel cells convert chemical energy directly into electrical energy without using a working fluid. The fuel (hydrogen) is oxidized at one electrode and the oxident (oxygen) is reduced at the other electrode. The electrons involved in these chemical reactions are routed through an external circuit providing electrical energy (see appendix G). The major advantages of this power system are:

1) Fuels are required materials at the lunar base
2) Fuels are recycleable
3) Yields potable water as a waste product
4) Operates at relatively low temperature (400 degrees F)

5) Few moving parts which could fail

Among the disadvantages are:

1) High weight of fuel and waste storage

2) Mission duration limited by fuel supply

(Ref. 4)

After evaluating the relative merits of each system, the isotope Brayton cycle stood out as the best option available. This system combines the advantages of the highest power output and the lowest weight offered by any system under consideration. The ability of isotope fuel source to provide power for up to 45 days of continuous service allows the vehicle to be considered for use in expanded roles on the lunar surface after only minimal modifications. Radiation shielding beyond that required by solar radiation will be provided to protect the crew from exposure, and the spent fuel packages could possibly be disposed of by launching them into space. This should not present an insurmountable problem as the gravity which must be overcome is only 1/6 that of the Earth.

4.4 MOBILITY

The locomotion solutions used in the original lunar rover still seem to offer the greatest number of advantages in lunar mobility. A driven track configuration was considered, but after investigation it was found that such a configuration would distribute the vehicle weight over too large an area and the necessary frictional forces are not achieved. It was found that wheels should be used instead of a track configuration because they serve to concentrate the vehicle's weight on a small area. This does create the required frictional force for propulsion. The optimal wheel diameter is being investigated, however, of the various wheel designs considered, an aluminum mesh tires of about 3-5 ft diameter offers the best combination of features:

1) Low weight

2) High strength and flexibility

3) Long service life

4) Shock absorption characteristics

This last feature is especially important due to the fact that satisfactory viscous vibration dampers suitable for lunar use have not been developed. Because of this factor and the low gravity on the lunar surface, the vehicle will be restricted to maximum speeds below 15 km/hr.

It has been determined that each wheel of the vehicle should be independently powered. the system provides the greatest traction, control, and system redundancy while providing the necessary power output. For the vehicle described, each of the four wheels would have a power requirement of approximately 2.5 hp in order to drive the vehicle and the power trailer. (5)

4.5 HEAT REJECTION

One of the greatest drawbacks of the isotope Brayton cycle is the fact that large amounts of heat must be rejected from the system. Some of this heat may be used to supply life support systems, but a much greater amount (about 8.6 kw) must be radiated to space. This function is preformed by cooling loops which transfer the heat to vapor fin radiators. this type of radiator is a duct, partially filled with a working fluid. One surface is externally heated while the other has the heat removed. Through evaporation, vapor flow, condensation, and fluid reflux, the duct acts as a heat transfer fin with an effectiveness of nearly 1. By proper selection of the working fluid, the internal pressure and weight of the fin can be kept to a minimum. THe area required for this radiator is 158 sq. ft. at a weight of about 110 lbs. (4)

5.0 CONTROLS

A sub-problem from the defined problem is the design of a controls system for the manned lunar mission. The requirements of this system will be to monitor the following:

* Navigation - drive station, wheel control
* Communication - base to vehicle, earth to vehicle
* Health/Environment Status - thermal control, O_2 availability
* Vehicle Status - fuel, temp., speed, and power monitoring

The manned lunar mission goal is to continue to develop and establish a topographic data base for computer vision of unmanned mission for third generation vehicles.

5.1 Navigation

The vehicle navigation systems primary purpose is to control vehicle speed, steering, stability and location. This is accomplished through monitors such as listed: radar, gyrocompasses, odometers and computer analysis. For navigation the following characteristics are very important: surface roughness, soil mechanics, and lighting. The lunar surface is primarily consists of low slopes, 4 - 6 degrees for 25 m ranges, although mountain slopes and crater can be as great as a 30 degrees incline (6). These areas will be avoided for actual vehicle travel. The topographical analysis have already been well developed through the Apollo missions which established photogeologic terrain assessment and high resolution vertical photography from the lunar orbit. In addition, physical properties of the soil are provided. In general, the soil is very loose at the surface and increases sharply within the first few inches (7). This is critical for determining vehicle travel (i.e. slip resistance and bearing strength). It is with this existing data that greater distances can be traveled with the available extended life support in a pressurized vehicle. The computer and radar map the vehicles' position to an internal map, this data, as well as communication stations such as antennas and satellites, provide the roving vehicle with enough information to travel to distances out of line of sight from the base.

The actual steering mechanism has a number of options available. Either direct rotation of wheels or changing ratio of rotation speed of the wheels are under consideration. The most suitable choice is the later since, "the absence of steerable wheels considerably simplifies the design of the vehicle, increases the net volume of the body, ensures a turn about the centre of the bearing surface and simplifies the motion control" (8). Six possible commands are used for the mobility of the vehicle - forward, backward, right and left hand motion at rest or during motion. The driver will be able control motion with a joystick type mechanism.

5.2 Communication

The necessity for communication is obvious. It is imperative that the lunar base know the status of the mission, and be able to provide emergency back-up if necessary. Since the lunar nodes have been established, these satellites can be use to rely signals using radio signals and computer monitoring. Furthermore, for shorter ranges rely antennas which establish a lunar grid system can be used as well. The antennas are implemented because there is no atmosphere on the moon, therefore signals can not be bounced. An antenna will be located at the rear exterior of the vehicle for receiving communication, vehicle-to-base and vehicle-to-earth.

5.3 Health & Environment Status

This area encompasses crew life support, cabin pressure, air purification, supplies (i.e. water & O_2) and thermal control. All status monitoring will be computerized with back-up gauges for emergency. A warning signal is initiated if any life support system should fail and any emergency back system will take over automatically or manually if desired for the crews safety. The cabin is maintained at atmospheric pressure for the comfort of the crew. The manlocks provided the decompression necessary to enter on to the lunar surface. This is a fail proof system through the provision of redundant systems which are incorporated within the manlocks. Extensive EVA support must be accounted for the experimental and sample gathering of the lunar surface. A maximum of three EVA events will occur for 5 - 7 hours periods, with only two crew members out at any one time. This then calls for approximately support for six EVA event plus emergency availability.

Air purification is a necessity for crew life support. The cabin consists of oxygen, nitrogen, small amounts of carbon dioxide, water vapor and trace gases (9). The carbon dioxide must be collected or recycled. For simplification the integrated non-recycling oxygen system was used a functional diagram can be seen in Appendix B, Figure B-2. This allows the waste heat from the power system to be utilized instead of electrical heat to filter (desiccant bed of silca gel) rather than recycled due to the additional power, weight and equipment which would be needed (10) (See Figure J-2 in Appendix J). Other life support requirements consists of water recovery, Figure J-3, and food management which are considered within the functional diagram. Emergency supplies are also provided.

As for the thermal control, both active and passive system are implemented. The passive control is from the structural design consisting of multilayer insulation between the two shells of the pressure vessel. This consists of columbium and copper foils interspaced with quartz. It is about 1.5 to 2.5 cm thick and will have a conductivity of about 0.002 watts per meter-Kelvin. In addition, a protective exterior coating, simply a white coating with a emissivity minimum of 0.8 and solar absorption of 0.3, will be used for reflection of solar and infrared radiation. The interior will therefore be completely isolated from the exterior shell. Power load will vary with the time of operation due to temperature changes which range from 365K - 200K (day & night temperatures respectively). As a result of the passive thermal control isolating the exterior, the active interior thermal control will strictly be based on the crew comfort. The active thermal control will be accomplished with a heat pump system which is incorporated into the power system. The system will consist of heat sinks, a cooling loop, and heat exchangers (i.e. exterior radiators). (11). (See Appendix A.)

5.4 Vehicle Status

Analog gauges, transducers, and thermocouples will be the primary sources to provide the status of the mechanical welfare of the vehicle which includes: Water levels & temperature, fuel availability, drive voltages and oil temperature & pressure. An Intel 8630 Analog Input/Output Processor converts the data. This same processor will be able to interface with the other vehicle components such as the drive voltages. (See Appendix B, Figure B-3 for functional diagram) (12). Included are emergency provision such as back-up supplies and in the case of a fire, a Halon Fire Suppression System will also be incorporated in the vehicles emergency system.

6.0 OPTIMUM CONCEPTUAL DESIGN

Over the past months, as many practical options for each lunar rover system as possible were taken into consideration. After careful consideration and detailed analysis (weighted property indices are included in appendix C), a single design configuration emerged, employing the best combination of options. This lunar roving vehicle, as designed, will be a pressurized vehicle capable of transporting a four man crew on an extended range mission lasting at least 3 days. It will have a double hull construction made of aluminum 7075-T6. There will be windows mounted in the front which will have a high efficiency anti-reflecting (HEA) coating to afford direct visual contact with lunar surface. The vehicle will be electrically powered with the energy provided by an isotope fuel source through a Brayton cycle power system which will be mounted on a trailer, separate from the main vehicle. This system will provide electrical energy to all onboard systems and will expel waste heat via vapor fin radiators. The majority of the control features will be taken directly from existing technology, however, it has been determined that the optimum steering control would be achieved through independently varying the rotation of each wheel. This combination of features will produce a vehicle which will not only meet the minimum requirement of being able to travel distances greater than 37.5 km, it will also be able to be adapted to a wide variety of missions for lunar scientists in the coming decades.

Could have used some functional diagram concept
Seem to have 'jumped to preconceived vehicle with internals
right away

7.0 CONCLUDING REMARKS

The conceptual design of the lunar vehicle will allow for the short to medium range missions (distances less than 500 km radius from base) and furthermore will have the capability to be adapted to a wide variety of other missions, since the power system can operate up to forty-five days. The first goal is establish the vehicle on lunar base and develop data base on the lunar surface such that the accuracy of the topographic mapping can be confirmed for future development of unmanned missions. Based on present studies, the lunar vehicle will be feasible, but further development and research is needed to verify assumptions. In conclusion, the pressurized roving vehicle will meet the necessary objectives through a three day mission which allows the crew to travel up to 150 km radius from the base at a speed of 10 - 15 Km/hr, with 15 - 20 hours of actual EVA activities available.

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APPENDIX A

SPECIFICATION LIST

GROUP: M. CLEMENS, L. WATLEY, R. LEACH

Updated 3/26/90

STATEMENT OF PROBLEM : Design a ground based vehicle that can travel longer distances (greater than 37.5km) from the base, with either manned or unmanned capabilities.

E- essential requirement

O- optional requirement

a - major

b - medium

c - minor

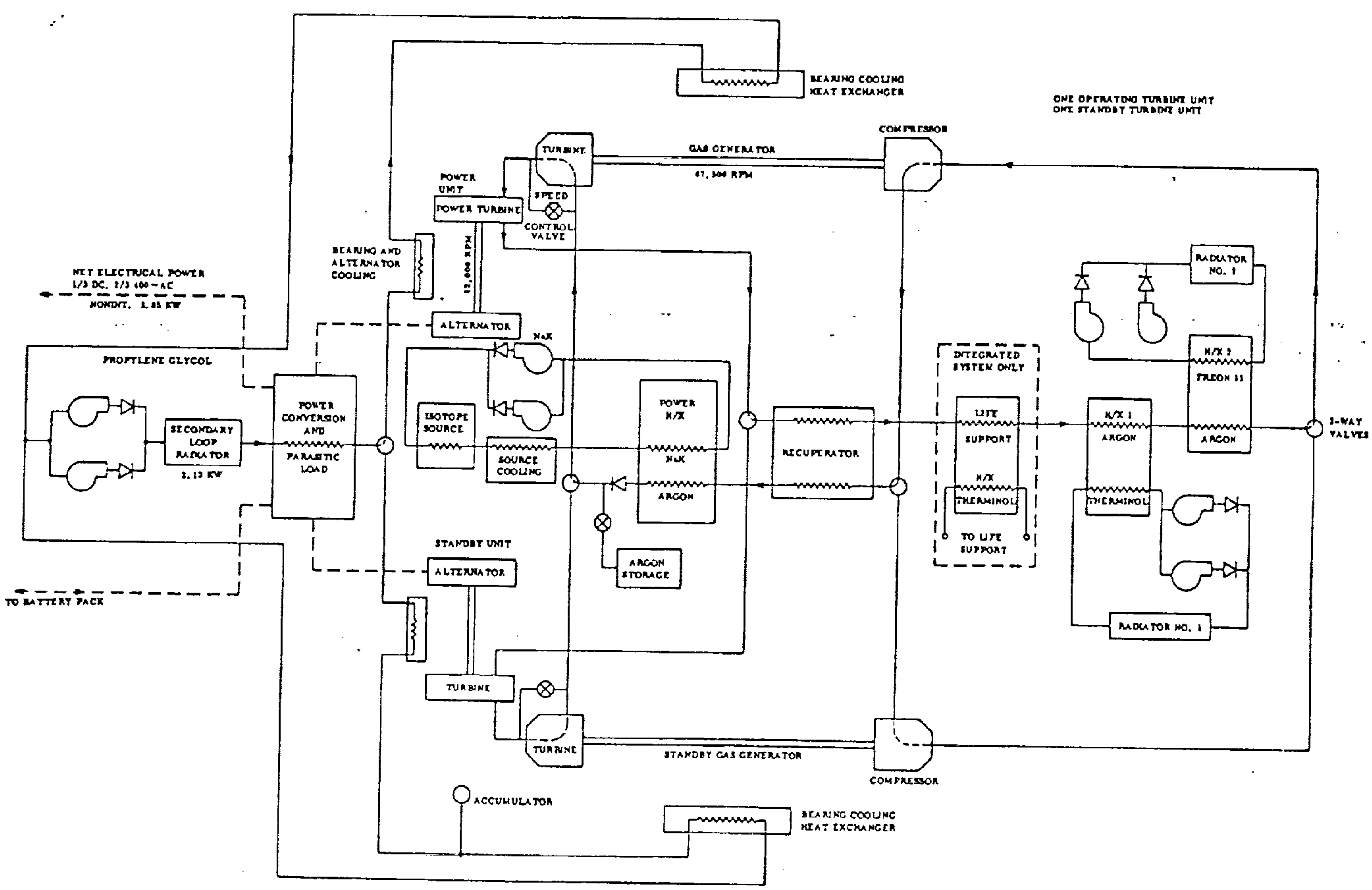
NO.	E/O	HEADINGS/INITIAL REQUIREMENTS
		Safety:
1	E	Emergency auxiliary power source
2	O-b	External/Internal lighting
3	O-c	Secondary driving station
		Ergonomics:
4	E	Pressurized cabin - 10-14 psi
5	O-a	(2) Man-lock type airlock system - 1m x 1m x 2m
6	E	Environmental control (i.e. heating/cooling system)
7	O-c	Storage space (i.e. waste, samples, etc)
8	O-a	Personal hygiene facility and waste processing
9	E	Windows
10	O-a	Docking fixture
11	E	Life Support (i.e. oxygen, water, food, and comfort)
12	E	Multilayer insulation (0.5 - 2.5 thick) and exterior surface coating (solar absorptivity max. 0.3 & infrared emissivity min. 0.8)
		Operation:
13	E	Manned vehicle
14	O-c	Unmanned capabilities
15	E	Individually powered wheels (4)
16	E	Suspension system (control vibrations)

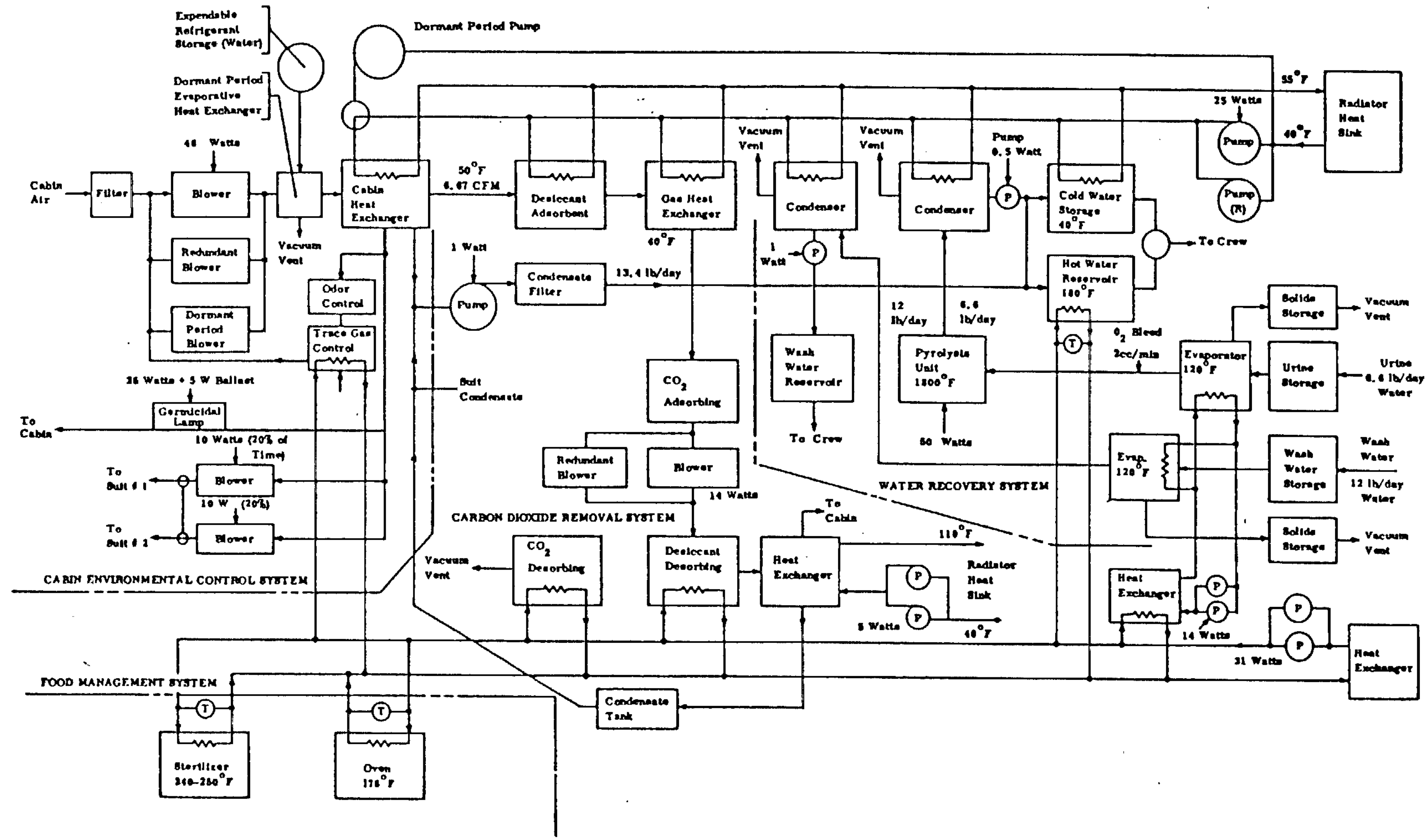
page 2 (Specification List continued)

NO.	E/O	HEADINGS/INITIAL REQUIREMENTS
		Operations (continued):
17	O-a	Night capabilities (including operation in lunar shadows)
18	O-c	Modular design (i.e. expand vehicle to increase capabilities)
		Signals:
19	E	Navigational instrumentation - gyrocompass and odometers for each wheel, antenna, exterior camera
20	E	Communication system - radio and electronic relay using lunar nodes
21	E	Control/Monitoring system - computerized (gauges as back-up)
		Geometry:
22	E	Structural efficiency - cylindrical vessel with semi-cylindrical ends - dimensions 9m x 3m x 3m
		Maintenance:
23	E	Protection system from lunar dust
24	E	Maintenance accessibility
		Energy:
25	E	Power supply independent of base - max. consumption 15,000 watts (Fuel cells or closed-cycle power system) with auxiliary available
26	E	Fuel storage or batteries
27	E	Individual power source for wheels - max. 6000 watts total
		Transport:
28	E	Multi-terrain capability - moderately rough, serious mobility obstacles and sharply defined features (20% grades)
		Kinematics:
29	E	Maximum speed 10-15 km/hr
30	E	Vehicle static stability (not less than 35 degrees) max. load 7000 kg
		Material:
31	E	Material considerations (to be investigated and developed) - Aluminum Alloy for double hull vessel - Fuel: H_2 and O_2, or Pu-238, Po-210, Cm-244 - Columbium & copper foils interspaced with quartz for insulation

APPENDIX B

FIGURE B-1
Brayton Flow Diagram

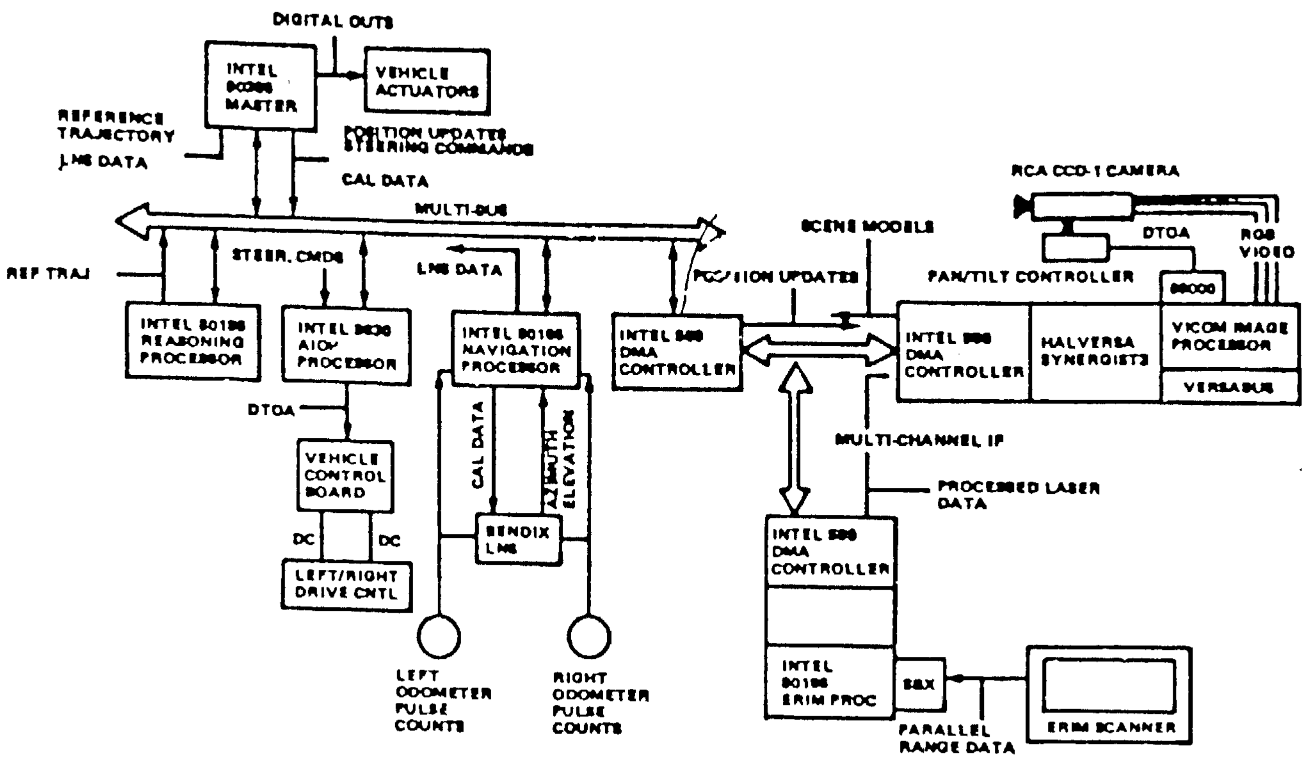




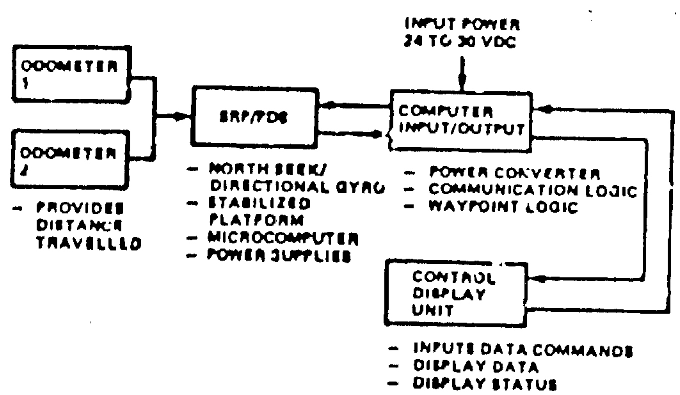
Block Diagram of Open Loop Integrated Life Support System

FIGURE B-2

INTEGRATED NON-RECYCLING OXYGEN SYSTEM



ALV simplified interface block diagram.



Demonstration system functional block diagram.

FIGURE B-3

NAVIGATION / CONTROL DIAGRAM

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE B-4 ALTERNATIVE DESIGN CONSIDERATIONS

SOLUTION PRINCIPLE		1	2	3
POWER SYSTEM	HYDROGEN / OXYGEN COMBUSTION			
	FUEL CELLS			
	ISOTOPE BRAYTON CYCLE			
LRV STRUCTURE	CYLINDER WITH SHERICAL END CAPS			
	CYLINDER WITH FLAT END CAPS			
	ELLPTICAL			
EVIRONMENT	NON-INTEGRATED SYSTEM WITH NO OXYGEN RECOVERY			
	INTEGRATED SYSTEM WITH NO OXYGEN RECOVERY			

APPENDIX C

TABLE C-1

WEIGHTED PROPERTY INDEX

For shell configuration

	Cylinder with spherical end caps	Cylinder with flat end caps	Non-cylindrical	Elliptical
Wall thickness needed (.3)	100	60	50	70
Space (.3) consideration	100	80	60	70
Weight (.1)	80	90	70	100
Stiffeners and reinforcements needed (.3)	100	50	50	90
shell configuration factors	98	66	55	79

How?

TABLE C-2

WEIGHTED PROPERTY INDEX
For outer shell material

	Aluminum composite	Carbon/graphite	Titanium	Stainless
Machine (.3) capabilities	100	50	80	80
Yield strength (.1)	70	100	80	80
Density (.2)	80	100	50	50
Strength/ weight (.1)	80	100	70	70
Cost (.3)	100	70	50	50
Total shell material factors	91	76	64	64

TABLE C-3

WEIGHTED PROPERTY INDEX
For power systems

		Fuel cells	Hydrogen/oxygen combustion	Isotope Brayton cycle
Reliability	(.1)	80	100	70
Availability of fuel	(.1)	80	70	100
Weight	(.1)	50	30	100
Maximum duration	(.1)	50	50	100
Safety	(.2)	100	80	60
Cost	(.2)	80	80	100
Disposal of spent fuel	(.1)	100	90	50
Power output	(.1)	60	60	100
Total system factors		78	72	84

TABLE C-4
WEIGHTED PROPERTY INDEX
For Steering Controls

		Direct Control	Variable Ratio Control
Reliability	(0.3)	100	80
Stability	(0.3)	80	100
Manuerbility	(0.2)	90	100
Mechanical Function	(0.1)	50	100
Cost	(0.1)	70	100
TOTAL SYSTEM FACTORS	(1.0)	84	94

TABLE C-5
WEIGHTED PROPERTY INDEX
For Thermal Control System

		Nonintegrated Systems, no O_2 Recovery	Integrated System, no O_2 Recovery	Integrated System w/ O_2 Recovery
Power Consumption	(0.1)	70	100	50
Weight Penalty	(0.3)	90	100	50
Efficiency	(0.3)	100	90	100
Equipment	(0.2)	90	100	80
Total Cost	(0.1)	80	100	60
TOTAL SYSTEM FACTORS	(1.0)	90	97	72

APPENDIX D

Pressure Vessel thickness Calculation

using a factor of safety = 4

too high!

$\sigma_{max} = 503317000$ Pa

$\frac{\sigma_{max}}{4} = 125829250$

Maxium Pressure inside cabin 101000 Pa

$d_i = 3$ m

$$\sigma_{max} = \frac{p(d_i + t)}{2t}$$

$$125829250 = \frac{101000(3+t)}{2t}$$

$$251658500t = 303000 + 101000t$$

$$t = 1.2 \text{ mm}$$

This is for a factor of safety of 4.

The thickness must be increased however to increase the protection from radiation.

APPENDIX E

TABLE E-1

* LUNAR ROVER SUBSYSTEMS COST ANALYSIS APPROXIMATION ($MILLIONS)

SUBSYSTEM	DEVELOPMENT	PRODUCTION	TOTAL
Inner Shell	$ 10.66	$ 1.24	$ 11.90
Outer Shell	10.84	1.26	12.1
Other Structure	19.04	2.49	21.53
Insulation	1.52	.297	1.182
Radiator	5.71	.861	6.571
Thermal pump	3.89	.254	4.144
Heat Exchanger	5.21	.305	5.515
Thermal System Piping	9.78	1.28	11.06
Hydrogen Tanks	3.49	.268	3.758
Oxygen Tanks	2.81	.211	3.021
Water Tanks	5.83	.472	6.302
Power Distribution	16.22	2.93	19.15
Wheels and Locomotion	13.9	2.36	16.26
Man Locks	32.53	5.3	37.83
Galley	13.08	1.22	14.3
Personal Hygiene	7.13	1.04	8.17
Emergency Equipment	1.20	.326	1.526
Life Support	48.36	8.40	56.76
Drive Stations	24.94	3.87	28.81
Work Stations	20.72	2.85	23.57
Sleep Quarters	4.24	.33 4.57	
Integration	16.24	3.16	19.40
Power Cart	12.0	5.0 17.0	
TOTAL	289.34	45.724	334.429

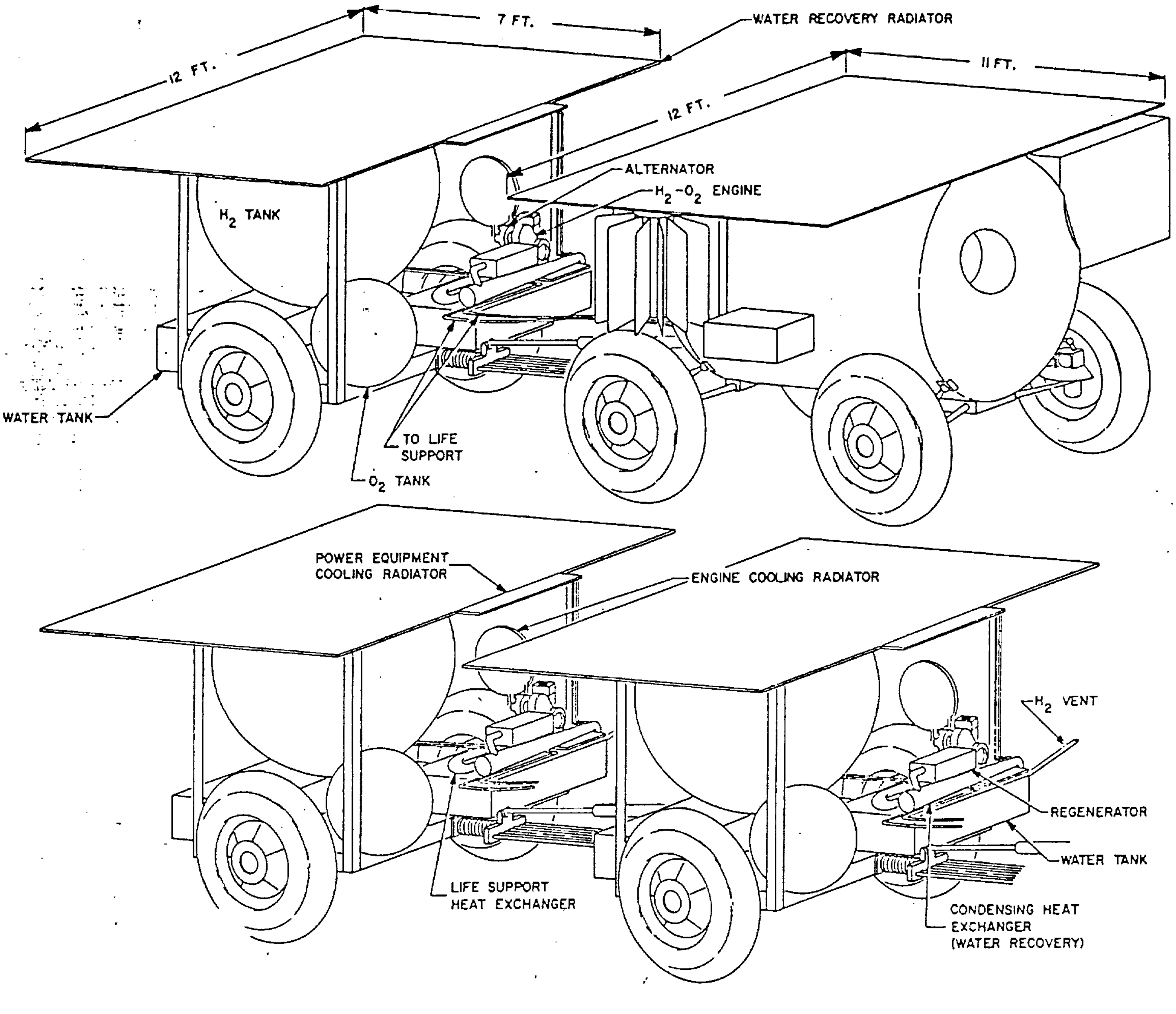
* REFERENCE (16)

APPENDIX F

HYDROGEN-OXYGEN COMBUSTION SYSTEM

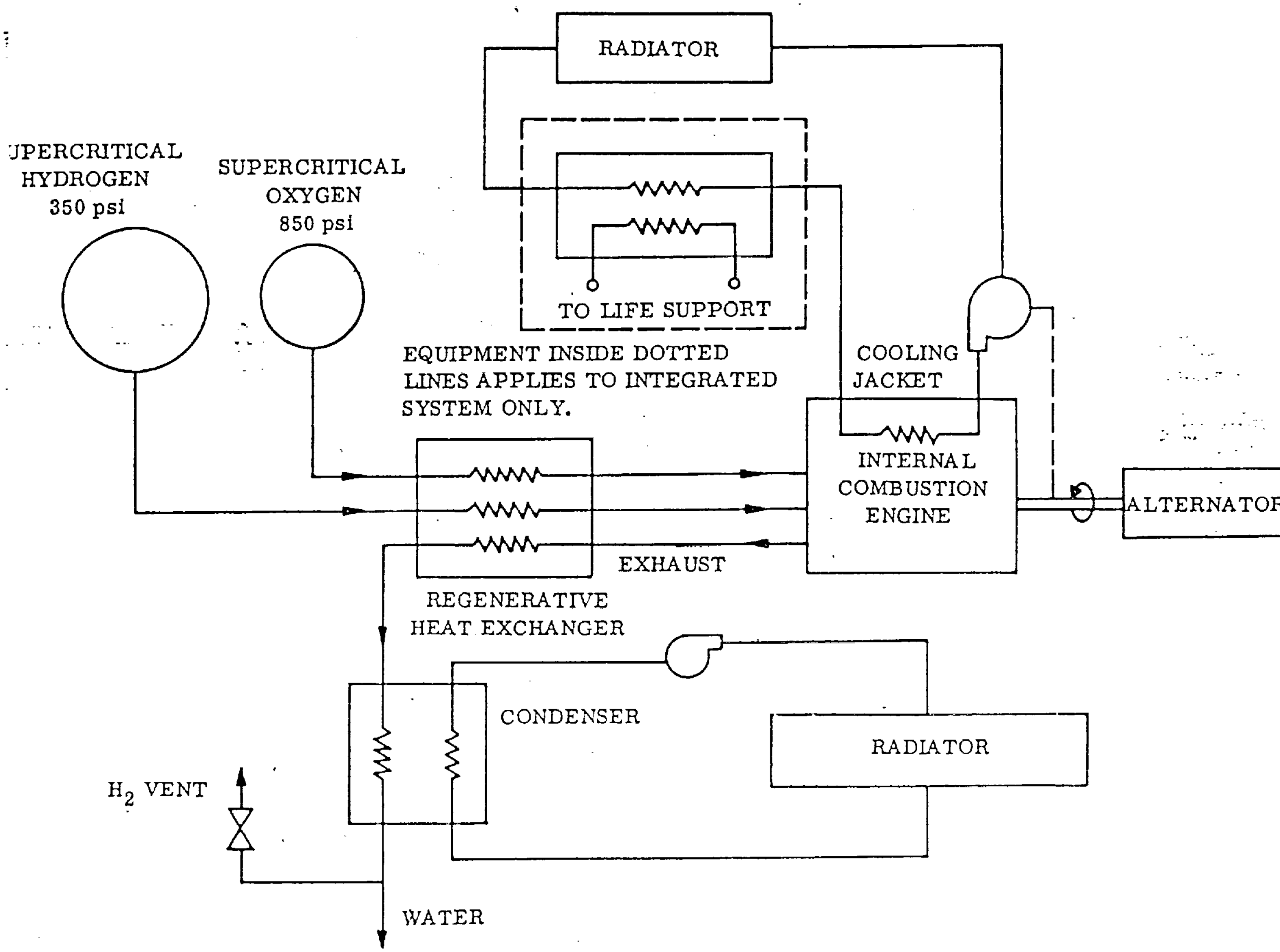
The hydrogen-oxygen combustion engine is a multiple cylinder,reciprocating engine using pressurized oxygen and hydrogen as fuel. The fuel elements are preheated prior to being admitted to the engine intake. Once forced into the cylinder, the gases are combined and compressed. Ignition is then initiated by an electric spark and the gases chemically combine, causing expansion and the release of energy which is converted into shaft work and used to turn an alternator. Hot exhaust gas in the form of water vapor is then used as the fuel preheater heat source before being routed to a heat exchanger where the exhaust water vapor is condensed and the waste heat carried to a radiator panel where it is radiated to space. The water condensate is then piped into a holding tank for later purification. Several identical power units must be used in parallel to maintain the necessary power output. Because this is true, at least three separate units having a total net weight of about 9000 lbs would be necessary to supply power for the entire mission.

FIGURE F-1
Hydrogen-Oxygen System Equipment



(ref 9)

FIGURE F-2
Hydrogen-Oxygen Engine Flow Diagram



(ref 9)

TABLE F-1

Hydrogen-Oxygen System Energy Requirements

Mission gross energy		1910 kw-hr
Net energy (one trailer)	1490 kw-hr	
Energy for two extra trailers	360	
Conversion Loss (ac-dc)	60	
Minimum gross power		0.60 kw
Average gross power		1.77
Maximum gross power		5.44

(ref 9)

TABLE F-2

Hydrogen-Oxygen System Weight

	System Weight (lb)		
Engine system, 3 at 80 lb			240
Radiators			230
Total propellant and tankage			6340
Hydrogen and H_2 tankage		2720	
Net hydrogen	1540		
Boil-off	370		
Insulation	330		
Tankage	480		
Oxygen and O_2 tankage		3620	
Net oxygen	3080		
Boil-off	280		
Insulation	90		
Tankage	170		
Total power system weight			6810 lb
Three trailers at 600 lb			1800
Life support oxygen			350
Gross power system			8960 lb
H_2 tank diameter = 7.12 ft			
O_2 tank diameter = 3.5 ft			

APPENDIX G

FUEL CELLS

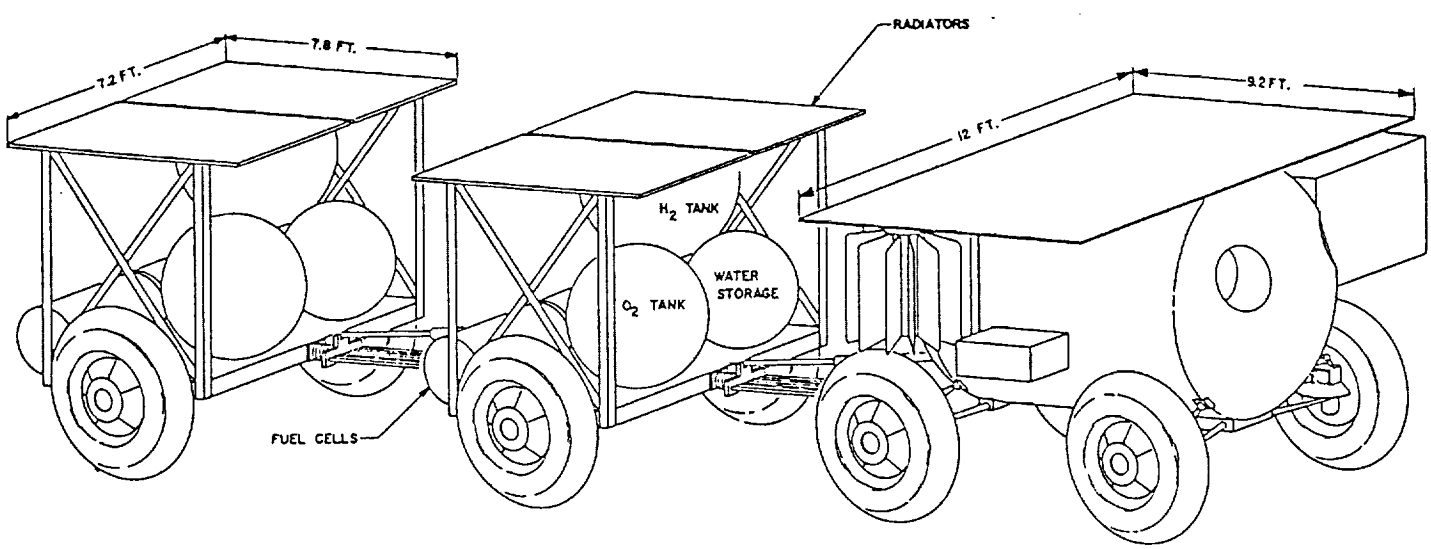
Fuel cells convert chemical energy directly into electrical energy without using a working fluid. The fuel (hydrogen) is oxidized at one electrode and the oxident (oxygen) is reduced at the other electrode. The electrons involved in these chemical reactions are routed through an external circuit providing electrical energy.

The fuel cell consists of the hydrogen side, the hydrogen regenerator, a temperature controlled bypass valve, a condenser, and a hydrogen pump. The fuel cells operate at a temperature of about 400 degrees F and use potassium hydroxide as an electrolyte. The electrodes are biporous nickel and nickel-oxide. The temperature of the hydrogen-water vapor regulates the hydrogen bypass valve which divides the exhaust gases, allowing part to pass through the regenerator before rejoining the remaining exhaust and passing through the condenser. The condenser lowers the temperature of the exhaust vapor, condensing the water into a liquid and separating out the remaining hydrogen gas. The hydrogen gas is then returned to the regenerator where it is heated prior to reentering the cell stack with the supply of fresh hydrogen from the storage tanks. The waste heat is transferred from the condenser to a space radiator using a closed propylene glycol loop.

In order to achieve a higher efficiency, it is desirable to operate the fuel cells at as constant a load as possible. Batteries may be used to help even out the load by recharging during low load periods and discharging during high load periods.

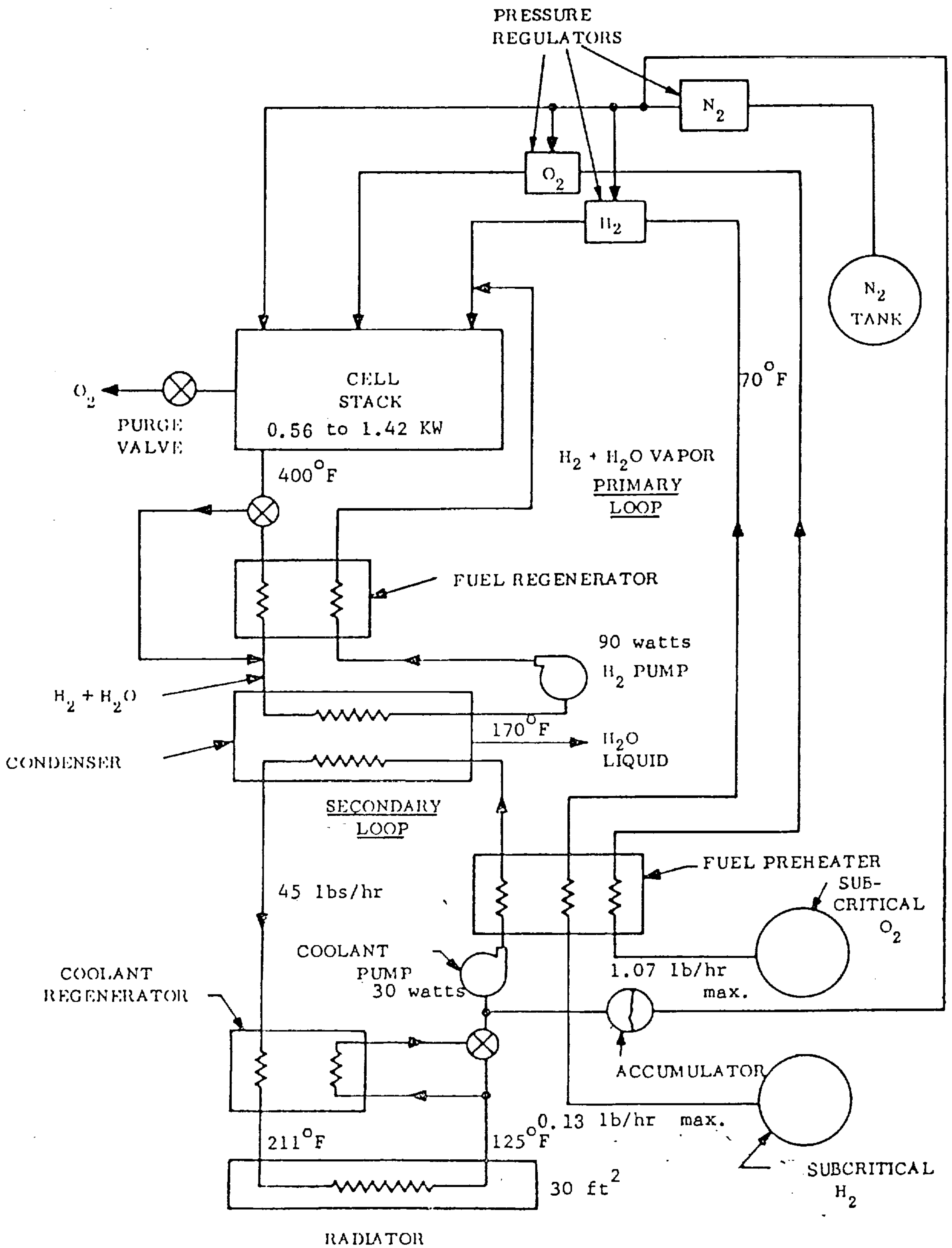
Due to the limited power output of each fuel cell (see table G-1), up to four cells, each mounted on a separate trailer, and having a total net weight of nearly 5000 lbs (as detailed in table G-2) would be necessary to provide the required power.

FIGURE G-1
Fuel Cell System Equipment



(Ref 9)

FIGURE G-2
Fuel Cell Flow Diagram



(Ref 9)

TABLE G-1

Fuel Cell Power Characteristics

Mission gross energy		3400 kw-hr
Mission net energy	2440 kw-hr	
Fuel cell parasitic loss	420	
Battery charge-discharge loss	175	
Power conditioning loss		
50% dc at efficiency of 0.92	140	
50% ac at efficiency of 0.087	225	
	3400 kw-hr	
Average gross power		3.15 kw
Number of modules (includes one standby)		4
Battery capacity		19.4 kw-hr
Minimum power output (3 modules)		2.60 kw
Maximum power output (3 modules)		4.26 kw
Module voltage at minimum power		28.8 volts
Module voltage at maximum power		27.1 volts
Average specific propellant consumption		0.824 lb/kw-hr

(Ref 9)

TABLE G-2
Fuel Cell System Weight

Module power plant weight, 4 at 223 lb			732 lb
Module plumbing, mounting, etc. 4 at 21 lb			84
Battery weight			390
Net propellant		2880 lb	
Hydrogen	320 lb		
Oxygen	2560		
Tankage		830	
Hydrogen	480		
Oxygen	380		
Total propellant and tankage			3740
Radiator weight, 4 at 11 lb			44
		Total	4990
Water production	2690 lb		
Weight penalty for extra trailer	600 lb		
H_2 Tank = 5 ft diameter			
O_2 Tank = 6 ft diameter			

(Ref 9)

APPENDIX H

ISOTOPE BRAYTON CYCLE

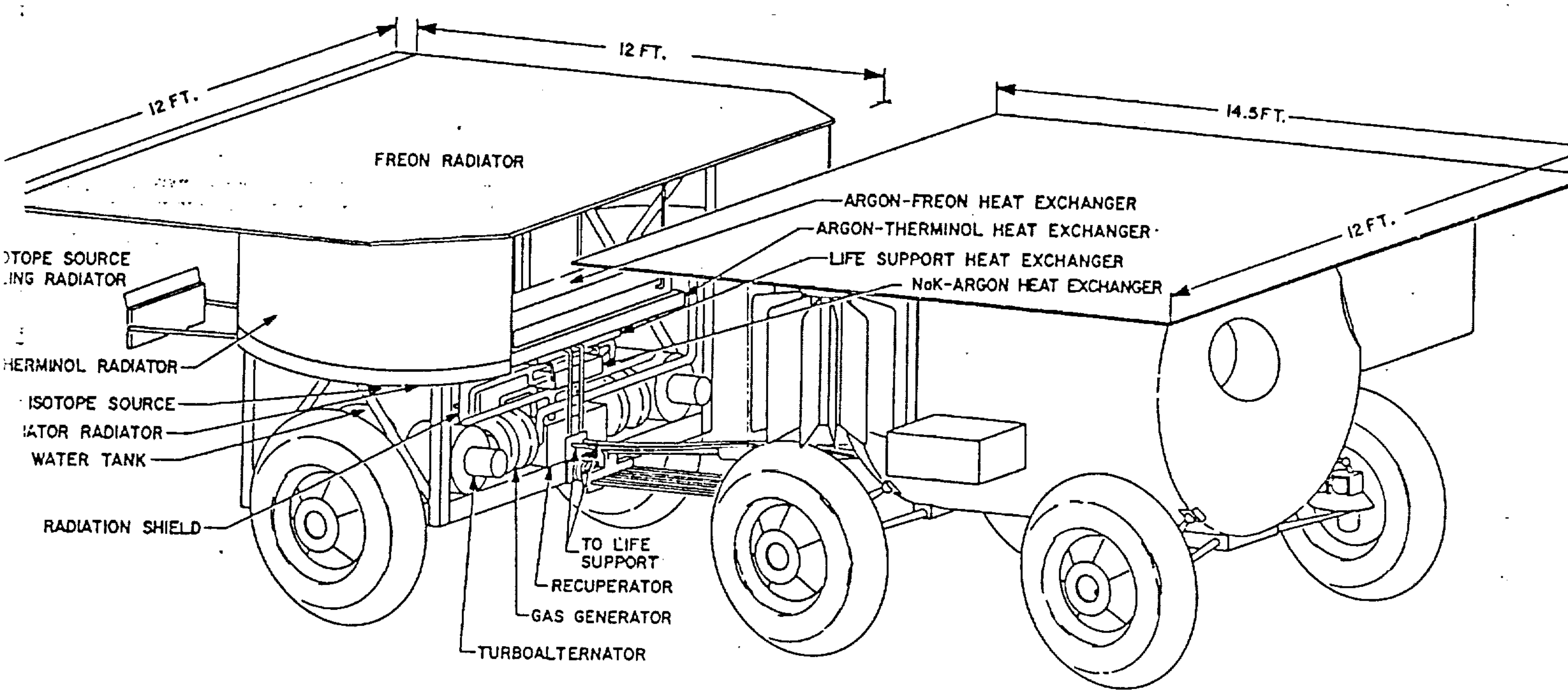
The closed loop Brayton power cycle consists of four separate loop systems. The argon gas loop is the workhorse of the system, gathering and transporting thermal energy to be converted into shaft work by the turbines. The sodium-potassium loop is used to transport thermal energy from the isotope fuel to the argon loop. The freon loop transfers waste heat from the argon loop to a radiator panel, and a propylene glycol loop used to maintain equipment operating temperatures. The argon gas loop, in it's principal task of gathering thermal energy, is first admitted into a two stage, biaxial flow centrifugal compressor. The biaxial flow configuration eliminates the need for thrust bearings and saves the associated energy lost to friction. From the compressor, the gas passes first through the recuperator, then through the power heat exchanger where heat form the isotope fuel is supplied by the NaK loop. The heated argon is then metered into the turbines. Two turbines are employed, each operating at a different RPM to provide power to the centrifugal compressor (@ 67,500 RPM) and to the alternator (@ 12,000 RPM). After expanding throug the turbines, the exhaust gas is then passed through the recuperator where excess heat is given up to the incomming argon gas. Further heat is then rejected to the freon loop for dissipation through a radiator panel. other heat exchangers may be included in the system to provide heat for environmental or equipment temperature control. After these heat exchanges, the argon is returned to the compressor inlet.

The isotope fuel may be either Pu-238, Po-210, or Cm-244. These isotopes can be packaged into convenient fuel modules which can be shielded to prevent crew exposure to radiation, and configured to eliminate the possibility of combining into a critical mass.

The fuel package for this system should be as self-contained as possible to eliminate the need for personnel exposure to radiation. A configuration like that shown in H-1 would contain not only the fuel material, but would also house the primary heat exchanger so that the only necessary connections would be the connections to the NaK fluid loop.

For a power system such as this, it is desirable to maintain the rate of energy generation at as constant a level as possible. Because the energy demands of the lunar rover vehicle will vary greatly, the power system load can be evened out by using excess energy to recharge battery arrays during low load periods. The stored energy can then be discharged to supplement the alternator output during high load periods. These battery arrays also serve as a source of emergency power in the event of a mechanical failure.

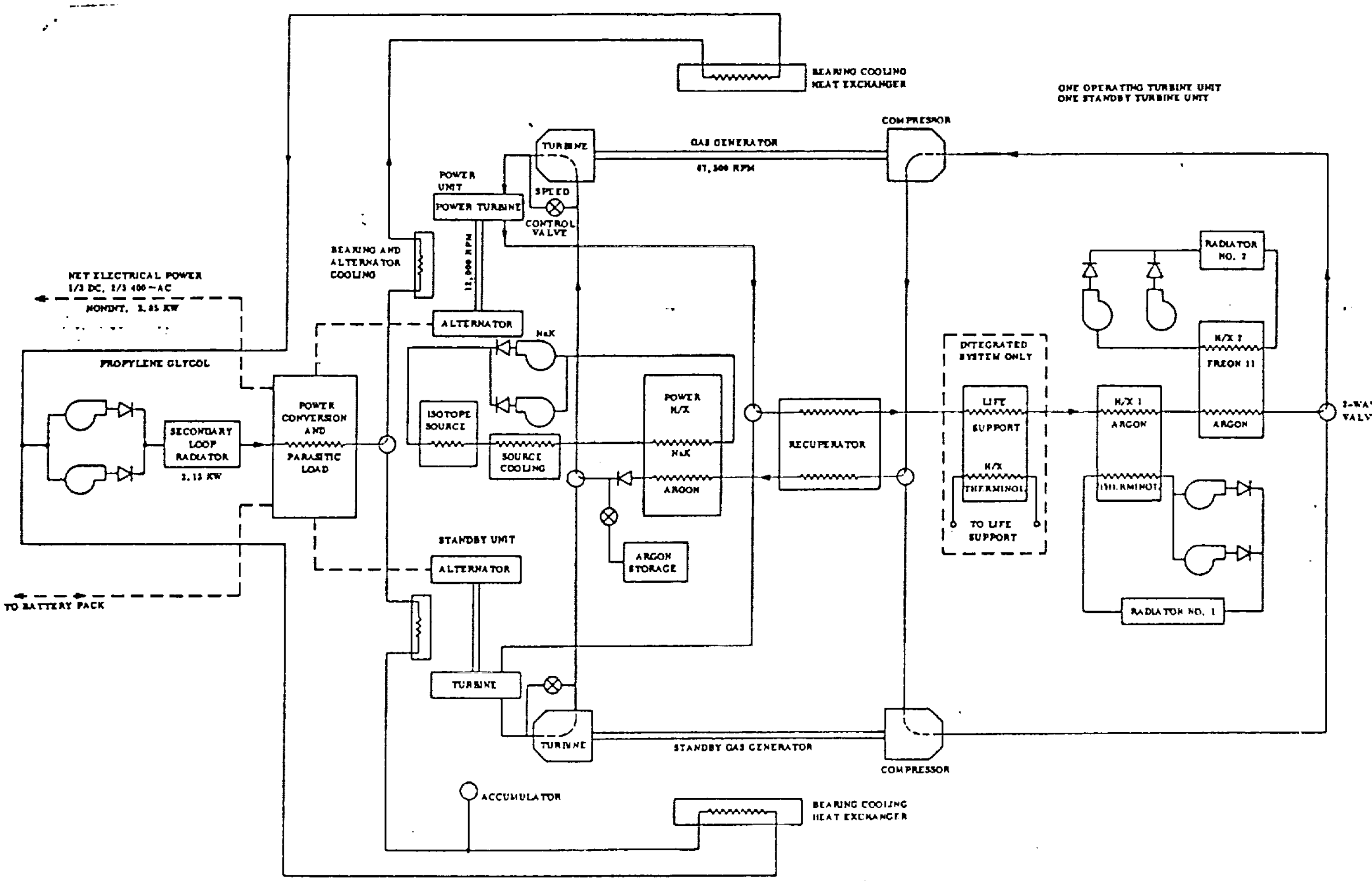
FIGURE II-1
Brayton Power System Equipment



(Ref 9)

FIGURE II-2

Brayton Cycle Flow Diagram



(Ref 9)

TABLE II-1

Brayton Cycle Power Balance

Electrical power out		1.88 kw
Radiation from secondary radiator		1.87 kw
Power conditioning loss	0.23	
Speed control	0.12	
Alternator loss	0.42	
Bearing cooling	1.10	
Battery heat loss		0.18 kw
Thermal power to life support		1.19 kw
Radiation from primary radiator		8.58 kw
Ducting thermal loss		0.20 kw
Total power out		13.9 kw
Source power required		13.9 kw

TABLE II-2

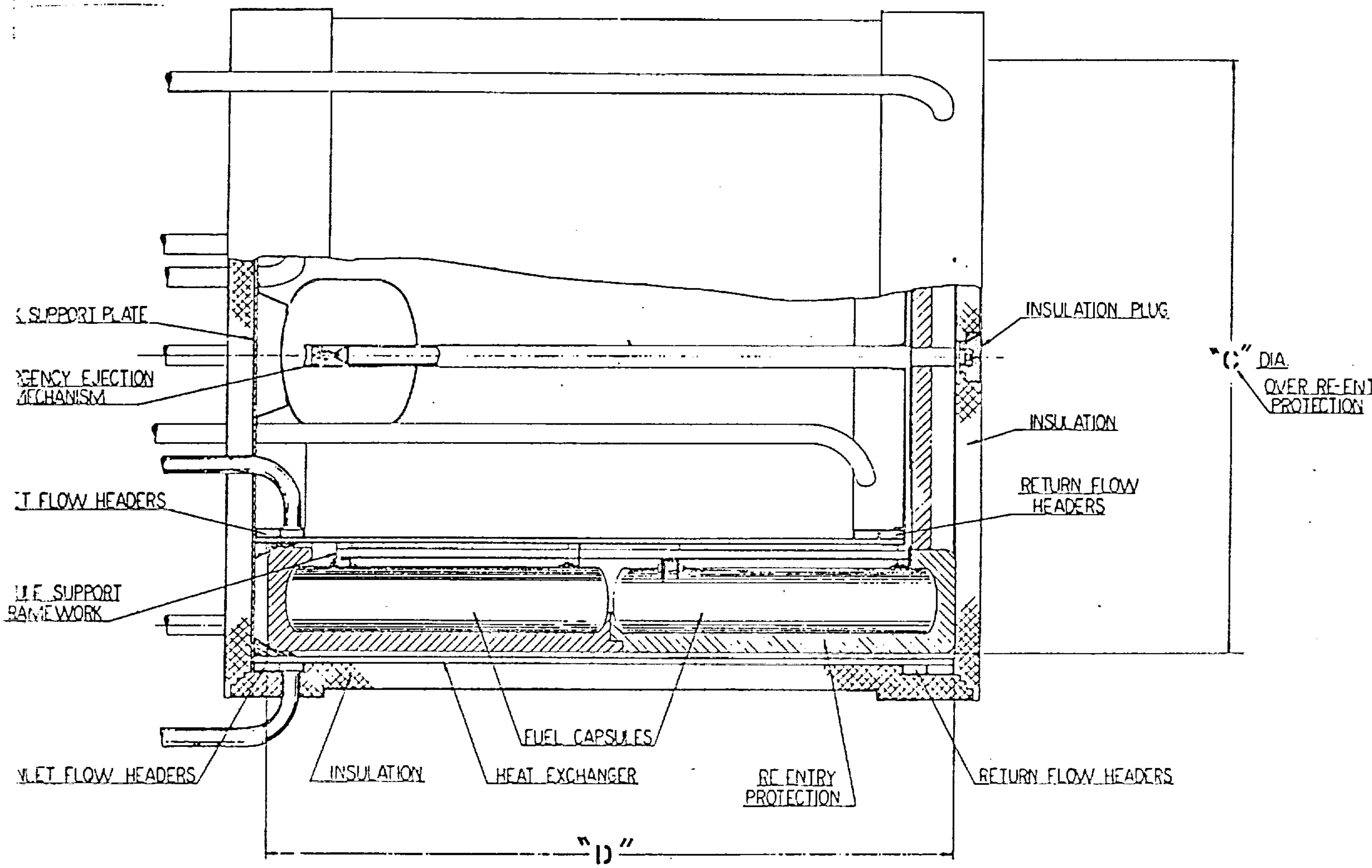
Brayton System Weight

Isotope source subsystem	795* lb
Turbocompressor (2)	68
Turboalternator (2)	88
Recuperator	110
Controls subsystem	80
Support structure and piping	210
Main radiators	86
Heat exchangers (heat rejection system)	33
Heat exchanger (life support)	15
Secondary heat rejection system	34
Power system weight	1519 lb
Water for suit cooling	750
Locomotion subsystem	600
Total trailer weight	2869 lb

*Approximate

(Ref 9)

FIGURE H-3
Fuel Package Diagram



(Ref 9)

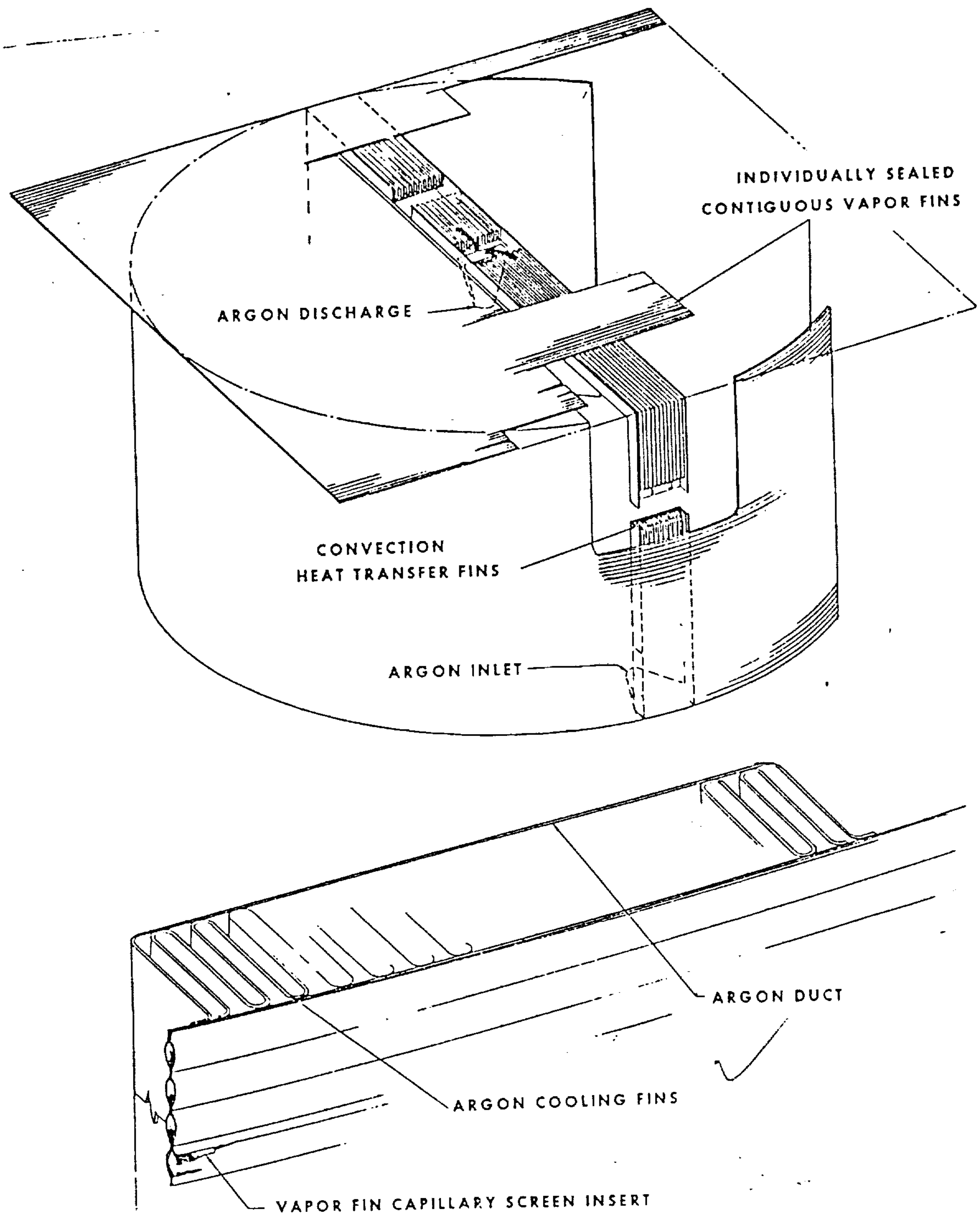
APPENDIX I

VAPOR FIN RADIATOR

A vapor fin radiator involves transferring heat from a closed loop to a working fluid causing the evaporation of the working fluid. It is critical that there be capillaries attached to both the surfaces of heat in flux and fluid condensation. A boiler pump is installed to evenly distribute the working fluid over the heat influx surface so as to minimize the temperature difference and maximize vapor generation. The surface may be a square weave screen in two layers with necessary venting for vapor removal. To ensure stream flow on a moving vehicle, the raditor is mounted at an angle of about 10 degrees. The vapor fin radiator allows the hot argon gas to enter from either side and is removed from the center. The internal fins receive heat by forced convection and conduct it to the fin outer wall surface which forms the vaporization surface. Each fin can operate at it's own temperature according to the temperature of the argon gas at that point. The fin then radiates the heat to the lunar surroundings.

FIGURE I-1

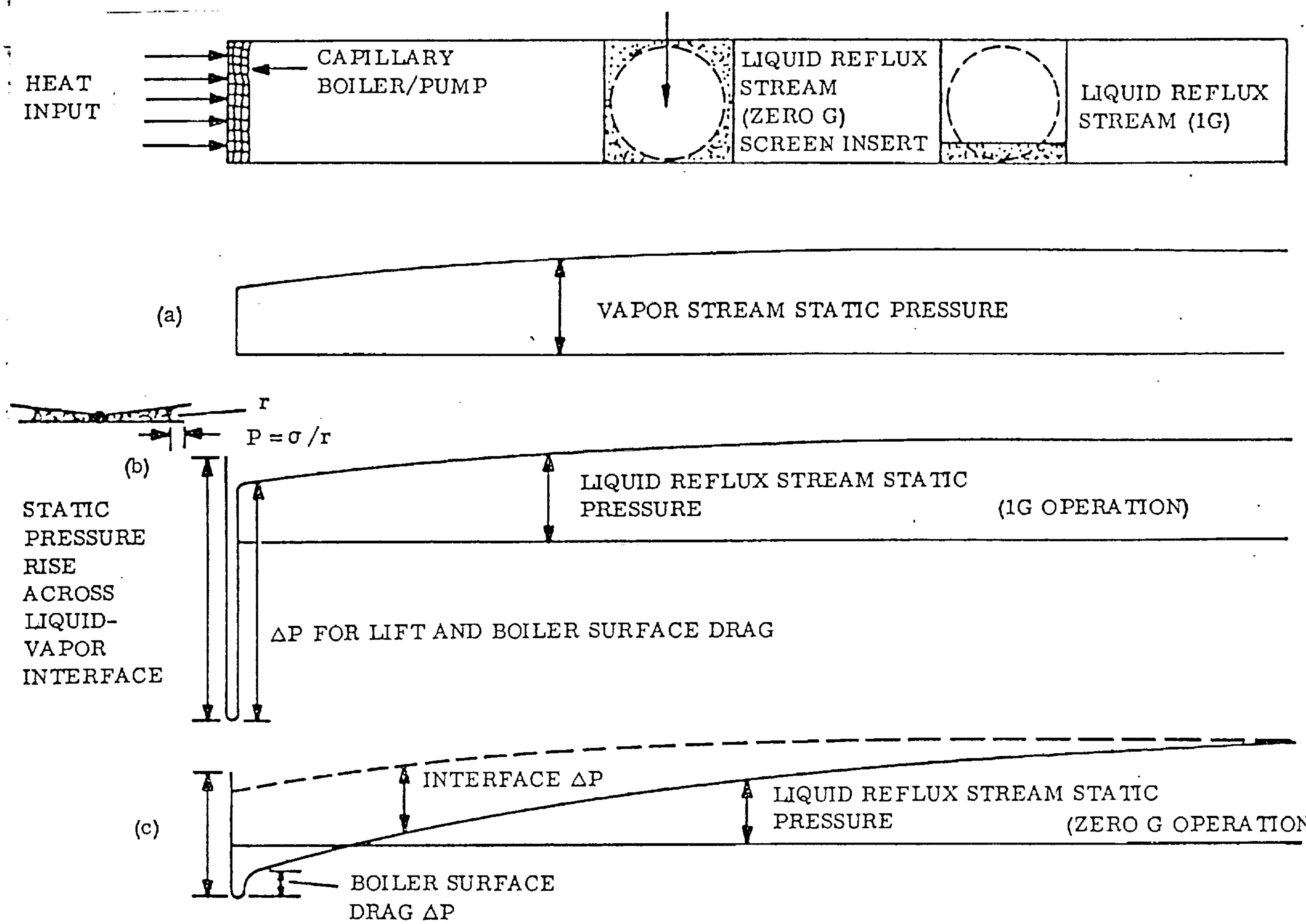
Vapor Fin Radiator Diagram



(Ref 9)

FIGURE I-2

Vapor Chamber Flow Dynamics

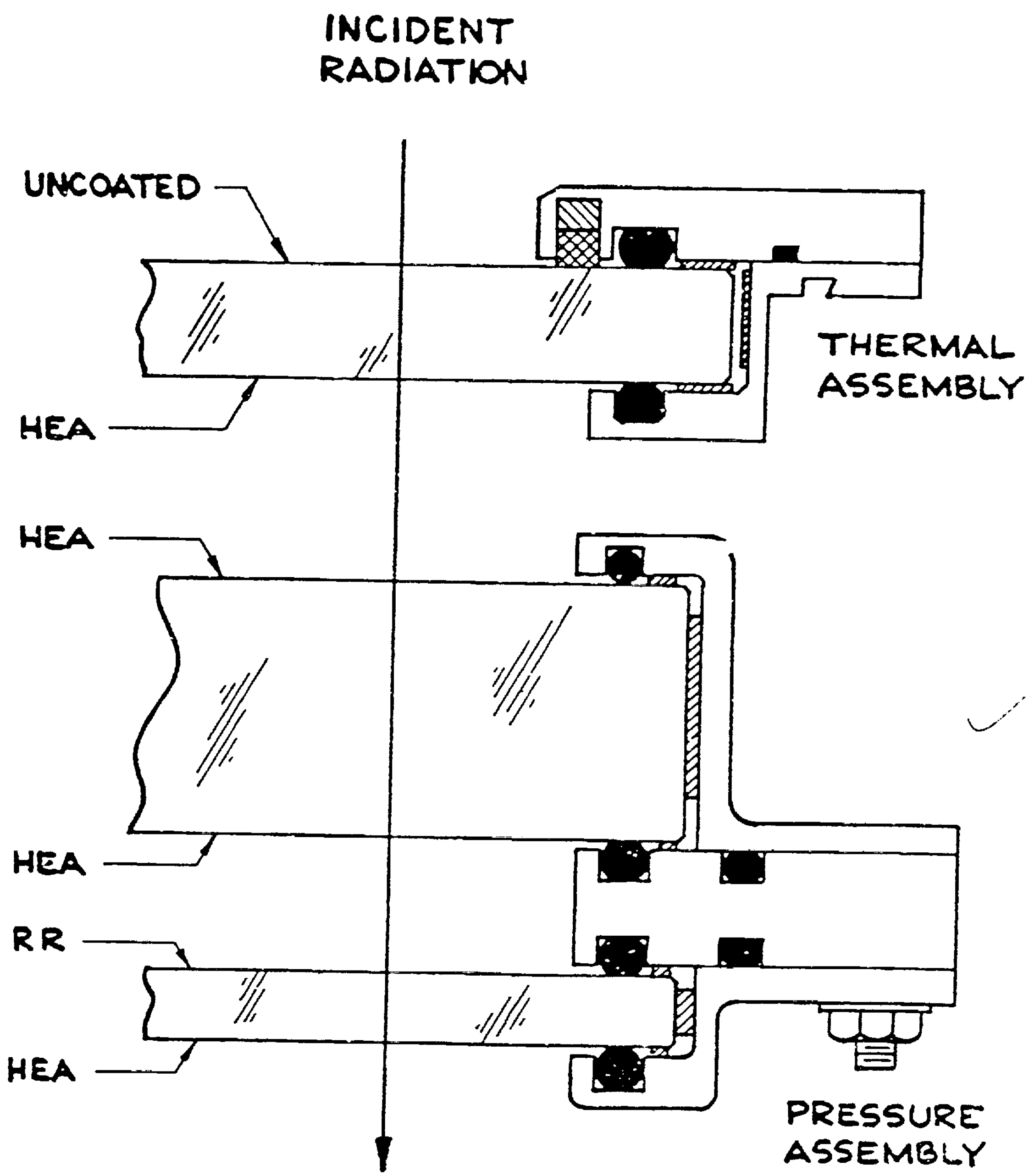


(Ref 9)

APPENDIX J

FIGURE J-1

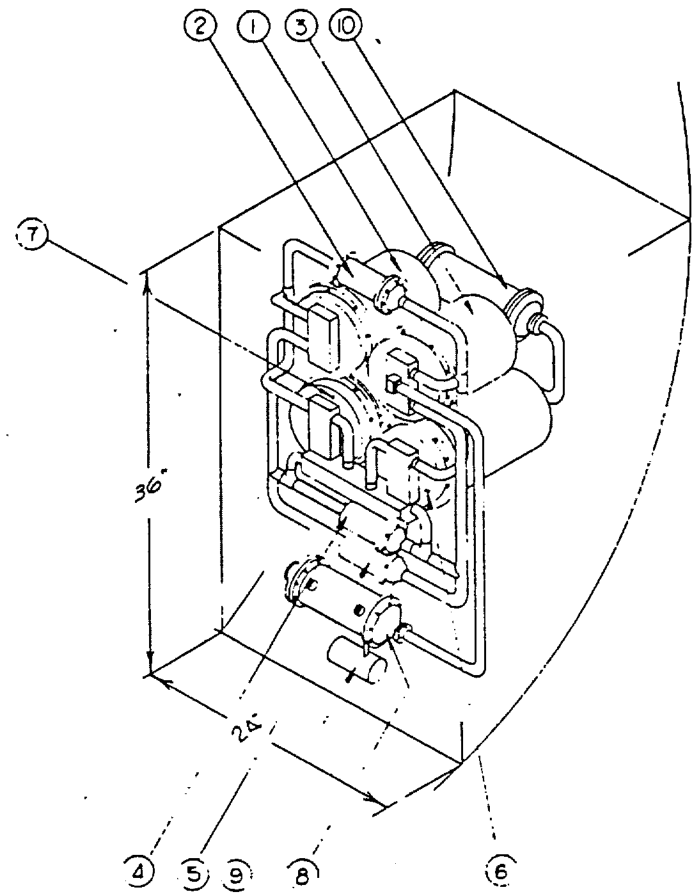
WINDOW CONNECTIONS



WINDOW SYSTEM

FIGURE J-2

CARBON DIOXIDE REMOVAL SYSTEM

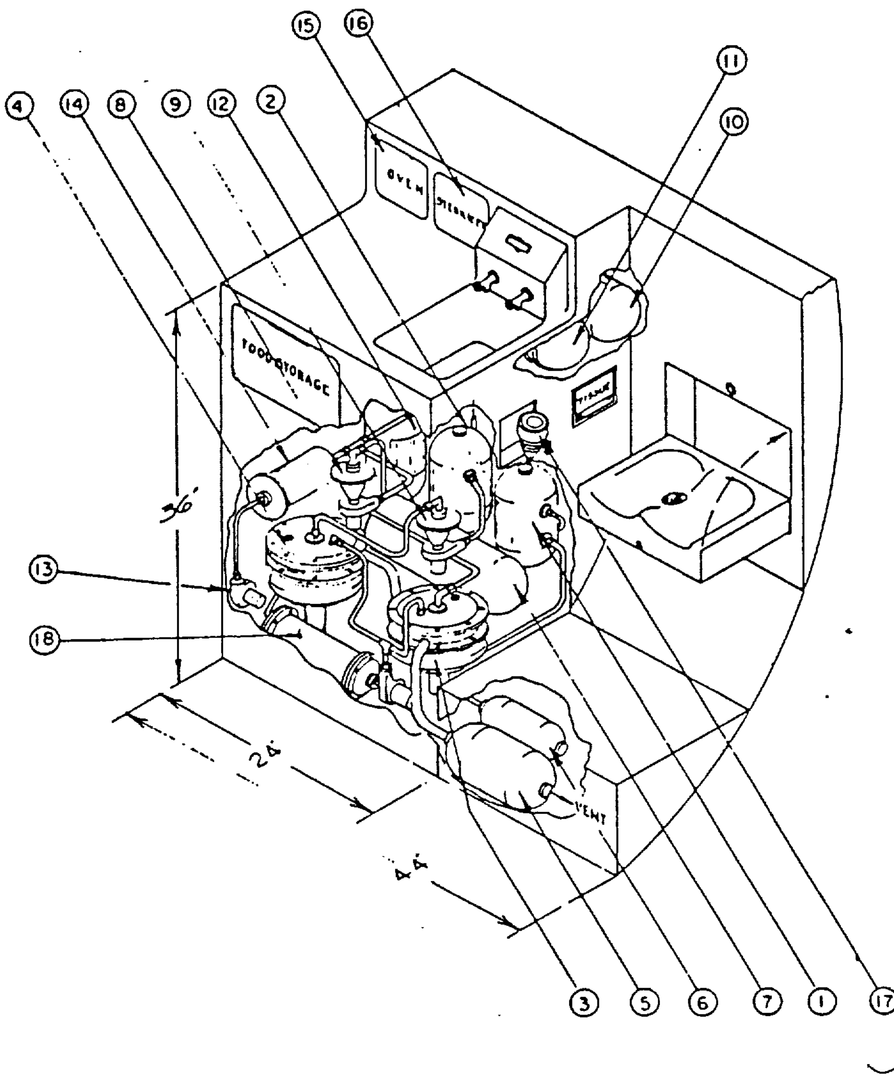


1 DESICCANT CANISTER
2 GAS HEAT EXCHANGER
3 DESICCANT CANISTER
4 BLOWER
5 REDUNDANT BLOWER
6 MOLECULAR SIEVE CANISTER
7 MOLECULAR SIEVE CANISTER
8 HEAT EXCHANGER
9 CONDENSATE TANK
10 HEAT EXCHANGER (THERMALLY INTEGRATED SYSTEM ONLY)

(ref 9)

FIGURE J-3

WATER RECOVERY SYSTEM



1 URINE STORAGE RESERVOIR
2 WASH WATER STORAGE RESER.
3 URINE EVAPORATOR
4 WASH WATER EVAPORATOR
5 URINE SOLIDS STORAGE
6 WASH WATER SOLIDS STORAGE
7 PYROLYSIS UNIT
8 POTABLE WATER CONDENSER
9 WASH WATER CONDENSER
10 POTABLE COLD WATER RESERVOIR
11 POTABLE HOT WATER RESERVOIR
12 WASH WATER RESERVOIR
13 PUMP
14 CONDENSATE FILTER
15 OVEN
16 STERILIZER
17 URINAL
18 HEAT EXCHANGER (THERMALLY INTEGRATED SYSTEM ONLY)

(Ref 9)

APPENDIX DD

Robotic Arm Design Project

by

Paul Mittendorff

Leonhard Parmeter

Gursharan Sohi

4/21/90

Submitted to Professor Chandrasekaran
FAMU/FSU College of Engineering

Abstract

This project was a group effort to explore the possibility of deploying a robotic arm on the moon. While the arm was initially conceived as a specimen gathering device to be fitted on to the lunar ARTS vehicle, it has been revised to satisfy a wider range of tasks.

The design of the Extendable Robotic Collection System (ERCOS) incorporates key issues like compactness, versatility, reliablity, accuracy, and weight. We developed a lunar robotic arm to effectivly deal with the harsh conditions on the lunar surface and provide great versatility to operations on the second generation lunar base.

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1.0 Introduction

In 1976, the viking lander landed on Mars. This lander incorporated the latest use of a robotic arm in a non-zero-g extraterrestrial environment. In Fact, this very apparatus was the major tool used to determine of life existed on Mars. Its principle function was the collection of martian soil samples. It accomplished this by use of an extendable scoop. Without this robotic arm, important information about Mars may never have been discovered.

ERCOS is a direct descendent of this system, for ERCOS's primary mission is similar. However, The ERCOS design will exhibit a more versatile and mobile solution to the early soil sampler of the Mars lander. The intention of ERCOS is to provide a second generation lunar base with a robotic arm that will not only be able to extract soil samples, but will provide an array of other services to the base as well. Due to its design, it will be attachable to a variety of platforms such as the lunar ARTS or at other stationary locations around the base. In short, it could be mounted anywhere a "big helping hand" is needed.

1.1 Problem Statement

Design a robotic arm to gather materials when the lunar arts is in the unmanned configuration.

2.0 Design Considerations

Since a lot of research and development is already available on various robotic arm designs,it was decided that the primary design task was to fully recognize the environmental differences brought about by the lunar environment and incorporate them into a final design. Furthermore, a high emphasis was placed on versatility and reliability due to the high cost and difficulties involved in transporting such a device to the moon.

To achieve a high degree of versatility, we decided that our specifications stipulate that our robotic arm have both a large workspace, and be detachable from the vehicle. Furthermore we decided that this robotic arm be able to manipulate high loads and still maintain a high degree of positional accuracy. See appendix (A) for full specifications.

Due to the particular nature of the operation of robotic arms, a number of initial assumptions must be made. Most tantamount of these was that the base frame of the robot be held stationary when the robotic arm is in operation. Secondly, the wrist assembly must be designed accommodate detachable end effectors for various operations. Thirdly, the vehicle which the arm will be attached to has sufficient sensors so as to accurately locate and orient the position of the robotic base frame within the desired workspace. With these assumptions met, we would be able to design a robotic arm to meet our specifications.

To help us formulate our design solutions, several function charts were made to further analyze the operational subsystems of the robotic arm Fig. (1) shows the final functional chart. All functional charts can be seen in appendix (B)

What follows is an explanation of the three design alternatives which we have considered. WE will briefly explain each design and elaborate on the design which we have selected by using weighted property indexes.

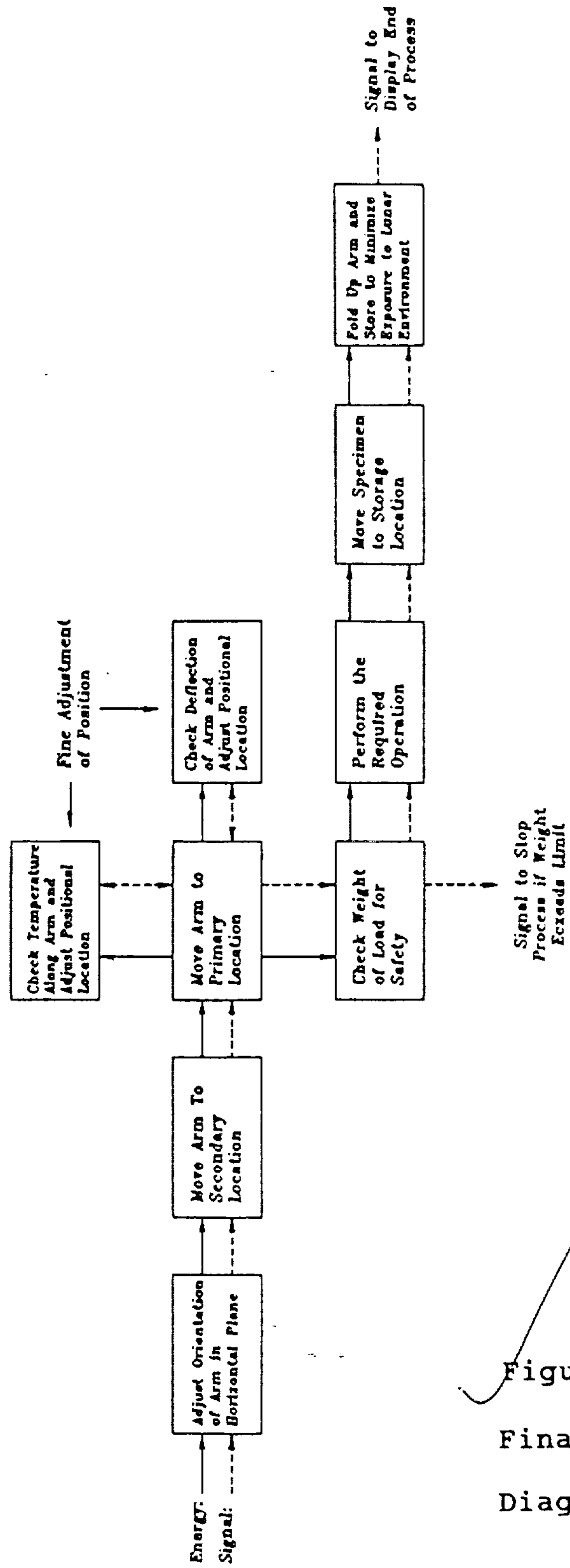

Figure 1

Final Functional

Diagram

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2.1 Design No. 1

The first design incorporates the use of all revolute joints. See Fig (2). This robotic arm is very similar to revolute robots used today on earth. This robotic arm would be composed of six links all connected by revolute joints. This would allow the robot to attain the full six degrees of freedom needed to obtain high versatility. It would be characterized by a rotating base connected to 2 long links in succession. To the end of these would be attached the wrist assembly which would be made up of 3 revolute joints connected is series in such a way that the axis of rotation for all 3 joints are orthoginal. The modular end effector would then be attached to the end of this.

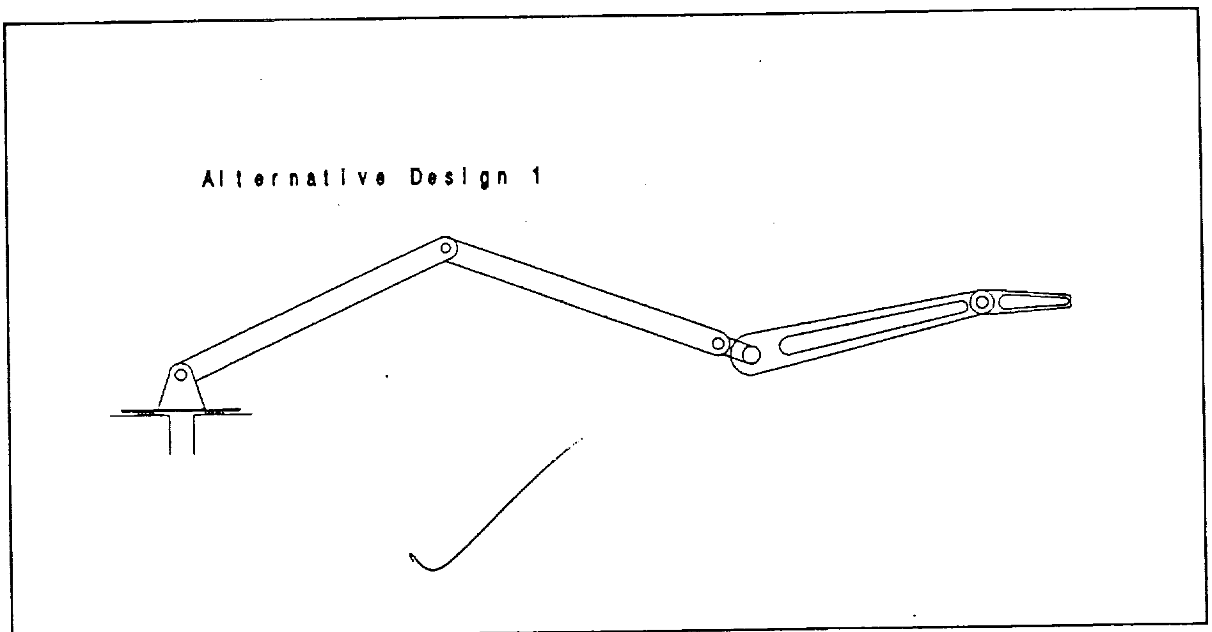

Figure 2 Revolute type robotic arm

Do you have a basis for arriving @ this configuration

2.2 Design No.2

The second design incorporates 6 links, and also attains 6 degrees of freedom. However, this robot is similar to a cylindrical coordinate robot. See Fig. (3). The primary difference between this design and design no.1 is the inclusion of a pair of prismatic joints to connect the first and the second link together, and the second to the third link. This is how the radial and Z axis locations of the end effector is controlled. This design would also contain the same wrist assembly as design no. 1.

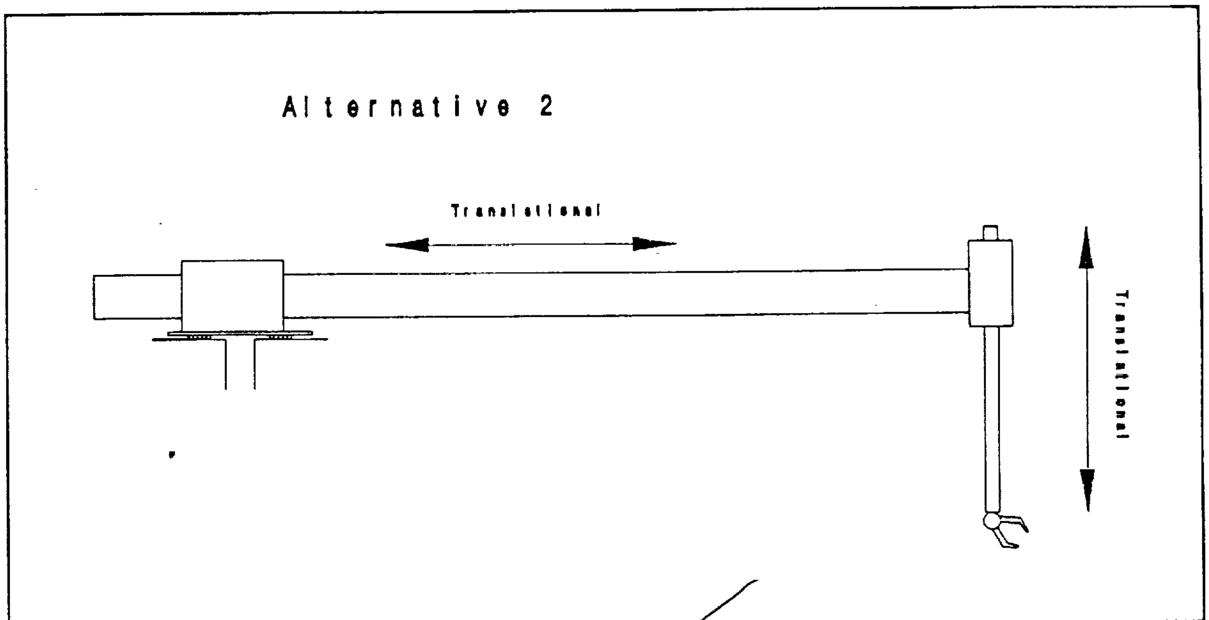

Figure 3 Prismatic joint robotic arm

2.3 Design No.3

The third design incorporates a combination of designs 1 and 2. See Fig. (4). It is composed of 9 links and also attains 6 degrees of freedom. It combines the concept of a revolute robot with links 5 through 9, and the concept of the cylindrical robot with links 2 through 5. As can be seen in Fig.(4), the second prismatic joint from design no.2 has been replaced by 2 revolute jointed links similar yet smaller than links 2 and 3 of design no.1. While the first prismatic joint of design no.2 has been replaced with a telescoping tower assembly.

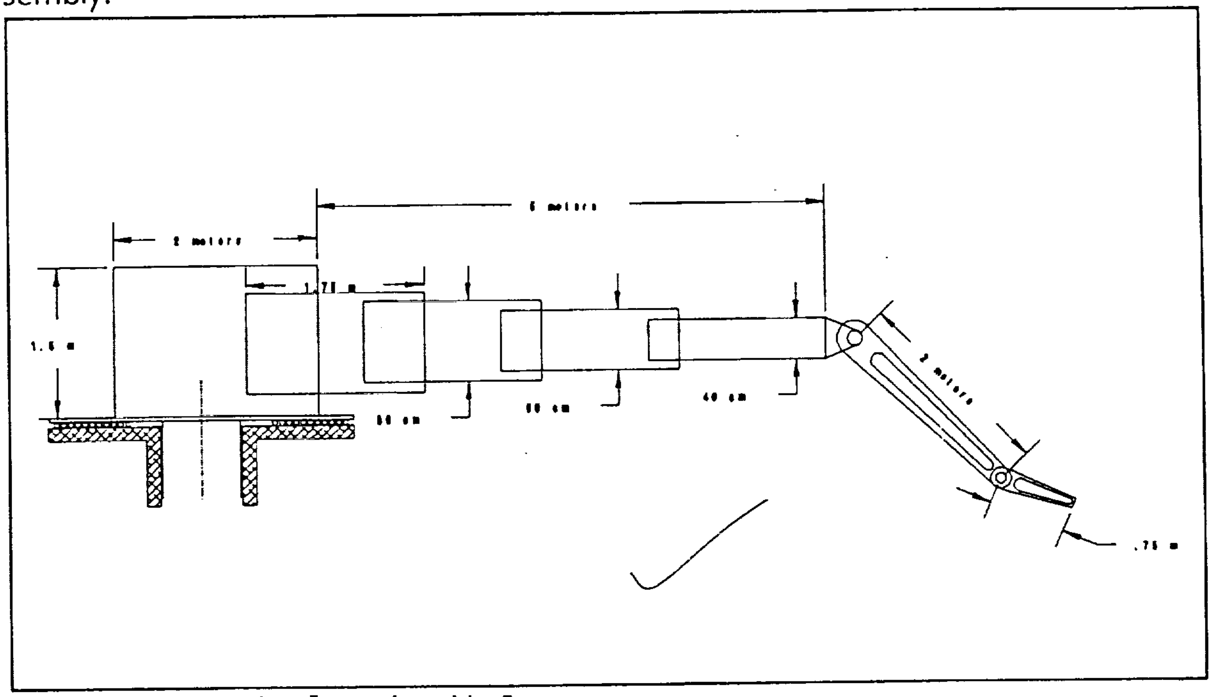

Figure 4 Design Configuration No.3

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3.0 Design Selection:

The robotic arm designs mentioned above have all been considered on the basis of the following criteria, and one design has been selected for further analysis.

1. Power requirements to provide motive force.
2. Compactness of design in storage condition.
3. Accuracy of positioning.
4. Range of workspace.
5. Range of positional solutions to avoid obstructions.

3.1 Weighted Property Index:

	Criteria 1	2	3	4	5	Total
	15%	30%	30%	10%	15%	100%
Design No. 1	1.5 / 10	3 / 10	3 / 10	9 / 90	7.5 / 50	24
Design No. 2	13.5 / 90	15 / 50	27 / 90	1 / 10	1.5 / 10	58
Design No. 3	7.5 / 50	27 / 90	15 / 50	5 / 50	13.5 / 90	68

Figure 5 Weighted property index

Based on this performance index, design no.3 was chosen upon for further development.

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4.0 Final Design Development

Design no.3 was the design configuration chosen for further development. At this point a material selection was needed. This again was accomplished by a weighted property index. See Fig. (6).

The final choice was aluminum 2014-T6. Our next step was to design the individual links and submit then to computer analysis based on the actual maximum forces and moments that they would be subjected to. Although our specifications called for a maximum static loading of 250 newtons, all computer analysis was performed under a loading of 500 newtons. This was done both to insure a greater factor of safety, and also to simulate the maximum loading that would occur when the load mass was accelerated at a rate of 1.635 meters/sec^2. This analysis allowed optimization to achieve our desired maximum deflections, maintain a high factor of safety, and reduce the overall weight of each link. At this point a compromise had to be made. This was between the radius of workspace and the positional error. We decided to reduce our radius of workspace from 7.75 meters to 7.31 meters so as to limit deflection from 6.2 mm to 3.055 mm. Our final structural dimensions are shown in the drawings in appendix C.

Criteria

Material:	1 Density 55%	2 Yield Strength 15%	3 E 13%	4 G 12%	5 Thermal Expan. Coeff. 5%	Total 100%
Steel: ASTM-A242	2.2 / 4 / 7860	6.3 / 42 / 345	13 / 100 / 200	12 / 100 / 79	4.2 / 84 / 11.7	37.7 / 330
ASTM-A514	2.2 / 4 / 7860	12.6 / 84 / 690	13 / 100 / 200	12 / 100 / 79	4.2 / 84 / 11.7	44 / 372
Stainless cold-roled	0.55 / 1 / 7920	9.45 / 63 / 520	12.35 / 95 / 190	11.04 / 92 / 73	2.2 / 44 / 17.3	35.59 / 295
Aluminum: 1100-H14	55 / 100 / 2710	1.8 / 12 / 95	4.55 / 35 / 70	3.96 / 33 / 26	0.05 / 1 / 23.6	65.36 / 181
2014-T6	53.9 / 98 / 2800	7.5 / 50 / 410	4.68 / 36 / 72	4.08 / 34 / 27	0.2 / 4 / 23.0	70.36 / 222
6061-T6	55 / 100 / 2710	4.65 / 31 / 255	4.42 / 34 / 69	3.96 / 33 / 26	0.05 / 1 / 23.6	68.08 / 199
Titanium:	36.3 / 66 / 4460	15 / 100 / 825	7.41 / 57 / 114	3.36 / 28 / 22	5 / 100 / 9.5	67.07 / 351

Figure 6 Weighted Material Index

4.01 Direct Conclusions

PAL computer analysis showed that to obtain the desired deflections under a loading of 500 newtons, the thickness of the tubes used in the lattice structure had to be as follows: (See Appendix C for Pal Models and outputs)

	Inner diameter	Outer diameter	Thickness
Lattice No.1	2.00 cm	3.50 cm	1.50 cm
Lattice No.2	3.00 cm	1.75 cm	1.25 cm
Lattice No.3	2.50 cm	1.50 cm	1.00 cm

Table I Lattice Tube Thickness

The total deflection at the end of the links was found to be:

Δ_1	-0.1064 mm
Δ_2	-0.3907 mm
Δ_3	-1.1830 mm
Δ_4	-0.7704 mm
Δ_5	-0.6025 mm
Total Δ	-3.053 mm

Table II Total Deflections

4.02 Design Calculations

Using the final dimensions as illustrated in appendix C, total volumes were calculated for each link of the ERCOS system. The results were as follows:

Link 1	$1.3935X10^{-2}$ m^3
Link 2	$1.1059X10^{-2}$ m^3
Link 3	$6.9431X10^{-3}$ m^3
Link 4	$1.1702X10^{-2}$ m^3
Link 5	$7.91X10^{-4}$ m^3
Total volume for links	$4.443X10^{-2}$ m^3

Table III Link Volumes

This plus the specified test loading of 500 newtons allowed the calculation of the maximum forces and moments that the ERCOS system would experience in a lunar environment. These results were then used to create the static loading conditions under which the PAL computer model was subjected.

Joint	Forces Downward	Moment clockwise
No.5	500.00 N	0.00 N*m
No.4	503.62 N	375.00 N*m
No.3	557.19 N	1060.8 N*m
No.2	588.98 N	1088.61 N*m
No.1	639.61 N	132.9 N*m
Base	703.4 N	1244.5 N*m

Table IV Forces and Moments at Joints

4.03 Environmental Considerations

Of paramount importance are the effects of heat on the ERCOS system. The greatest effect that it would have on the robotic arm is the expansion and contraction of the links in the system. However, as we know the thermal expansion characteristics of the material that the links are made of,this can be compensated for. This can be done by placing thermal sensors at even increments along the links and using their output in the controller program to control the actuators to maintain positional certainty. As for the heat buildup, the arm itself can act as a thermal conduit to conduct the heat back to the base where a system can be devised to reject it.

Another major concern generated by the environment is that of abrasive lunar dust. It will be very important to completely cover the joint actuator to keep dust out. A Nylon bushing can be utilized to seal the link shafts so no dust can penetrate. As to protecting the lattice structure, this can be accomplished by placing a housing over it so that when it is in its retracted mode it is completely sealed. During operation, the vehicle will be stationary therefore the dust can not be kicked up high enough to impact with the lattice structure.

As for meteorite bombardment, no vulnerable components will be left exposed. Also, the exterior of the link arms and lattice structures will be coated with a high temperature silicon padding. This padding will be much like the anechoic tiles used on today's submarines. This padding would then be painted in a high emissivity white aluminum paint to help with heat dissipation.

4.04 Signal Transfer

The electrical signal input and output from the various sensors on ERCOS will all be located within the circumference of the base joint. The transfer contacts will be made up of a series of concentric rings on the underside of the ERCOS system. These rings will then come into contact with a series of brush contacts located on the mounting base of whatever the ERCOS is to be mounted on. As the diameter of the base joint of the ERCOS system is 1 meter, it would be an easy matter to install several hundred signal connections this way. Furthermore, this method allows the ERCOS system a full 360° of rotation. See Fig.(7).

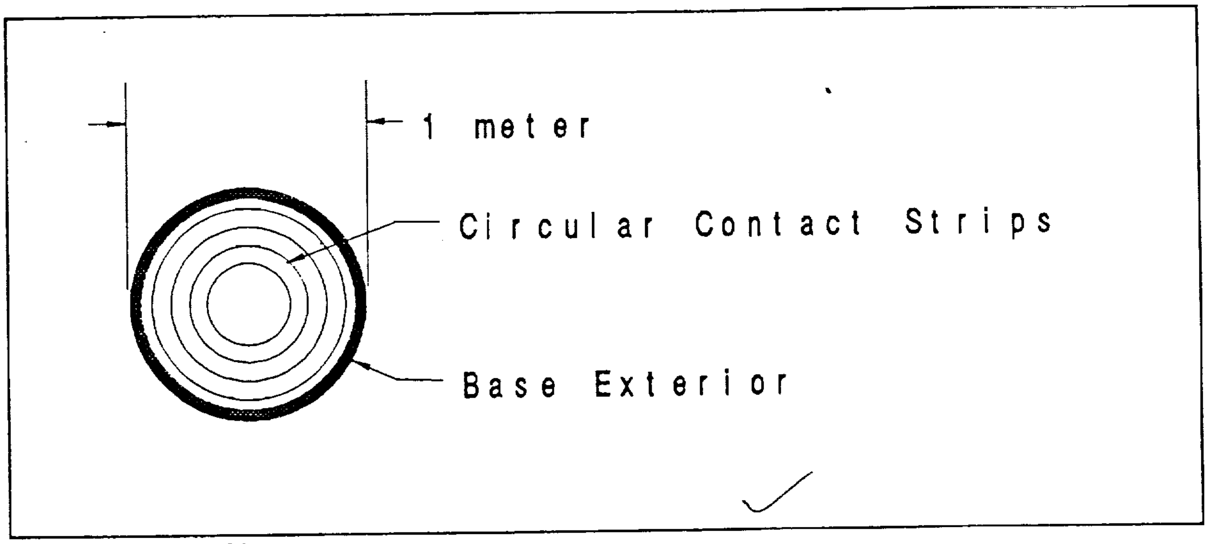

Figure 7 Base Diagram

4.05 Final Configuration

This final configuration is composedof a three link lattice structure, a two link revolute joint arm structure, and a rotational base through which the signal throughput is done. The base also has a housing that will protect the ERCOS system when not in operation.

Fig.(8) also shows the extent of the robotic workspace, as well as the position of the various links when ERCOS is in storage mode.

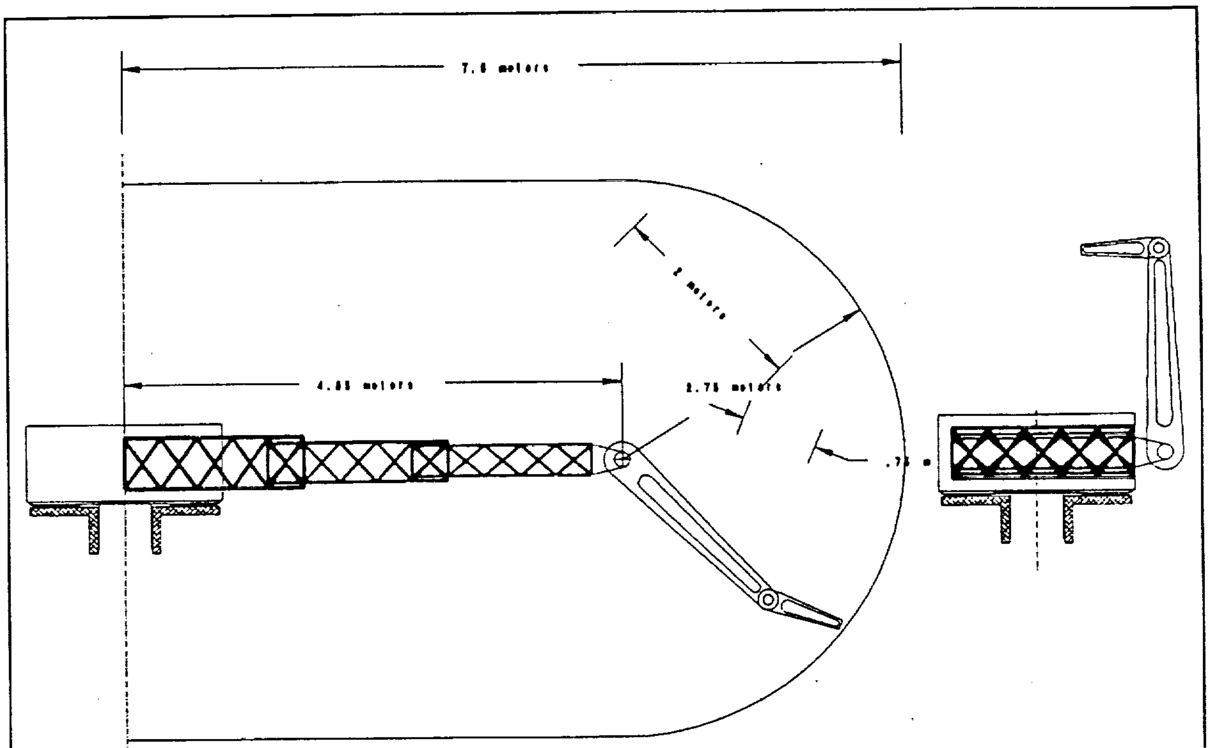

Figure 8 Final Configuration of ERCOS

A more thorough design schematic can be seen in appendix C

4.06 Conclusion

The Final design of ERCOS enabled key issues like compactness, versatility, and reliability to be addressed. By incorporating extendible links into ERCOS the goal of compactness was achieved. The extendable links retract into to house when the robotic arm is not in use: thereby enabling ERCOS to be protected from lunar dust. The extendible link also enable an easy access to the whole structure. Furthermore, a PAL2 analysis of the ERCOS structure revealed a maximum deflection of 3.053 mm at the end effector. The stresses were calculated by Von Mises stress theory this indicated a high factor of safety and thus a high reliability.

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Appendix

Appendix A

Specifications

SPECIFICATIONS

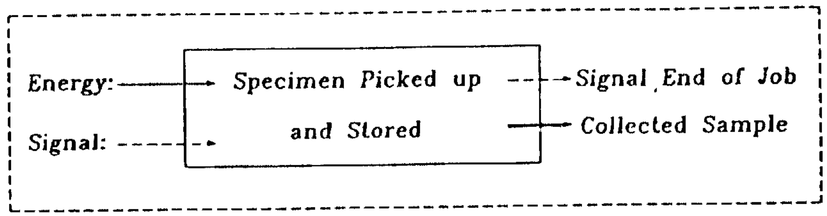
NO.	E/O	REQUIREMENTS	COMMENTS
1	E	HORIZONTAL REACH max 8.0m min 0.25m	reduced to 7.6m 3/28/90
2	E	VERTICAL REACH max 4.75m min 0.00m	
3	E	RETRACTED HEIGHT :2.5m	
4	E	RETRACTED WIDTH :2.0m	
5	E	MOTION TYPES lattice structure (trans) end links(2) (rot.) wrist (bi rot.) housing (rot.)	
6	E	MAXIMUM DEFLECTION :2.0mm	CHANGED TO 4mm or LESS 3/28/9
7	E	MAXIMUN LOAD : 225 N	
8	E	MAXIMUN WEIGHT : 750 kg	
9	E	POWER CONSUMPTION (max) 700kw	
10	E	MATERIAL TYPE: AL 2014T6	
11	E	COMPENSATING SYSTEMS: thermal deflection	closed loop
12	E	DRIVEN SYSTEMS: electrical	

Appendix B

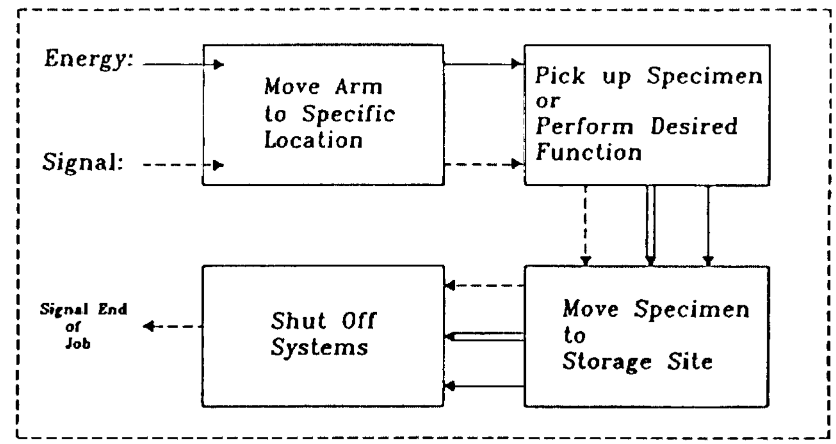
Function Diagrams

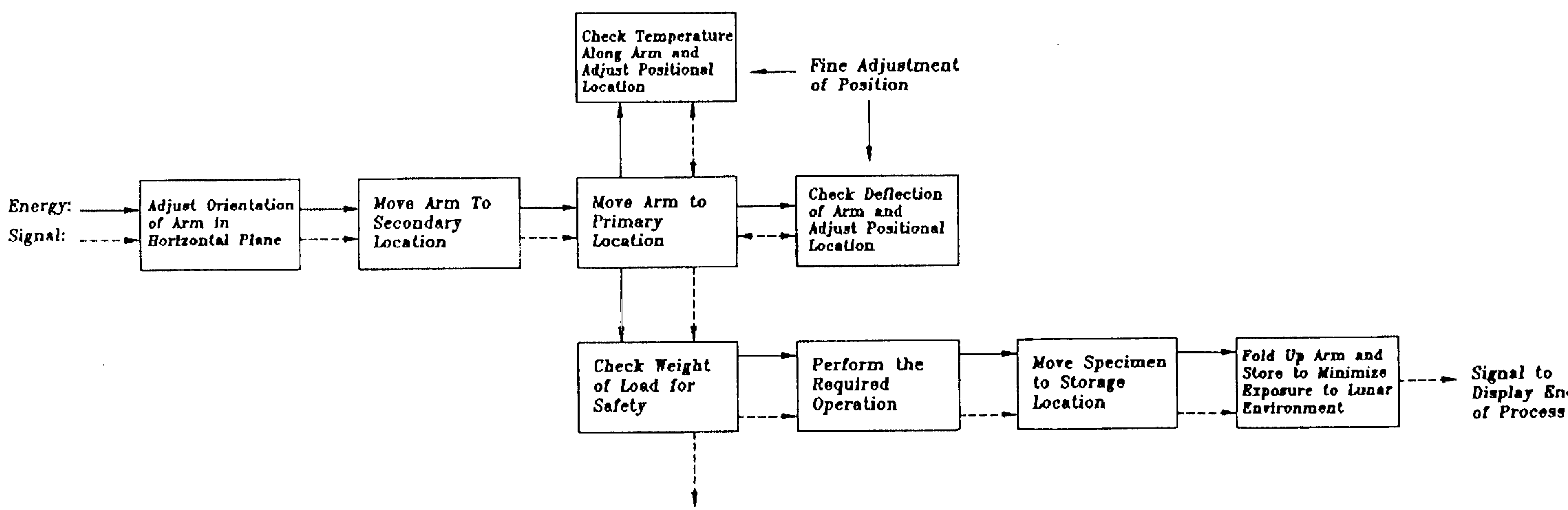
Functional Requirements:

Robot Arm: Preliminary Function Chart



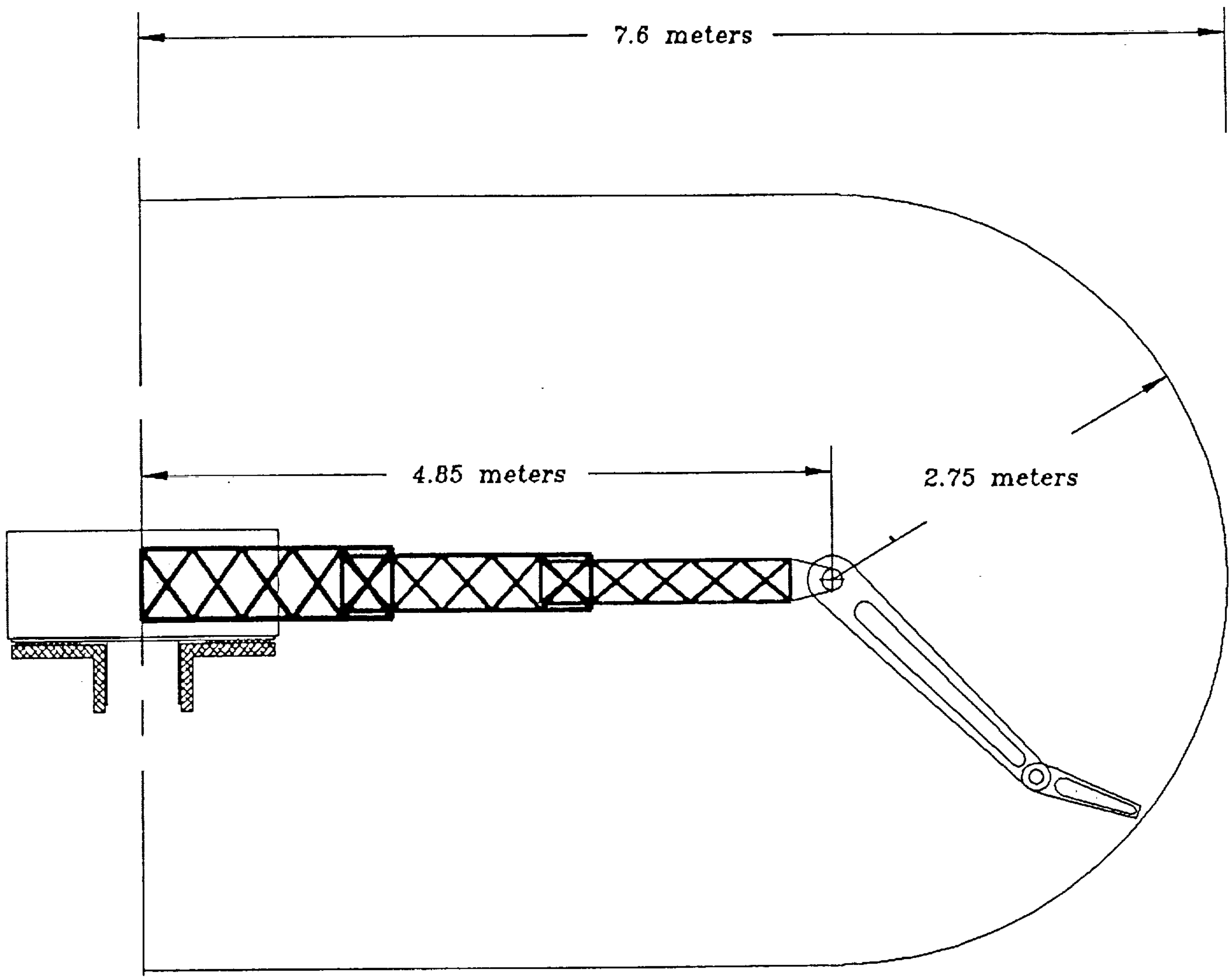
Robotic Arm: Sub Level 1 Function Diagram

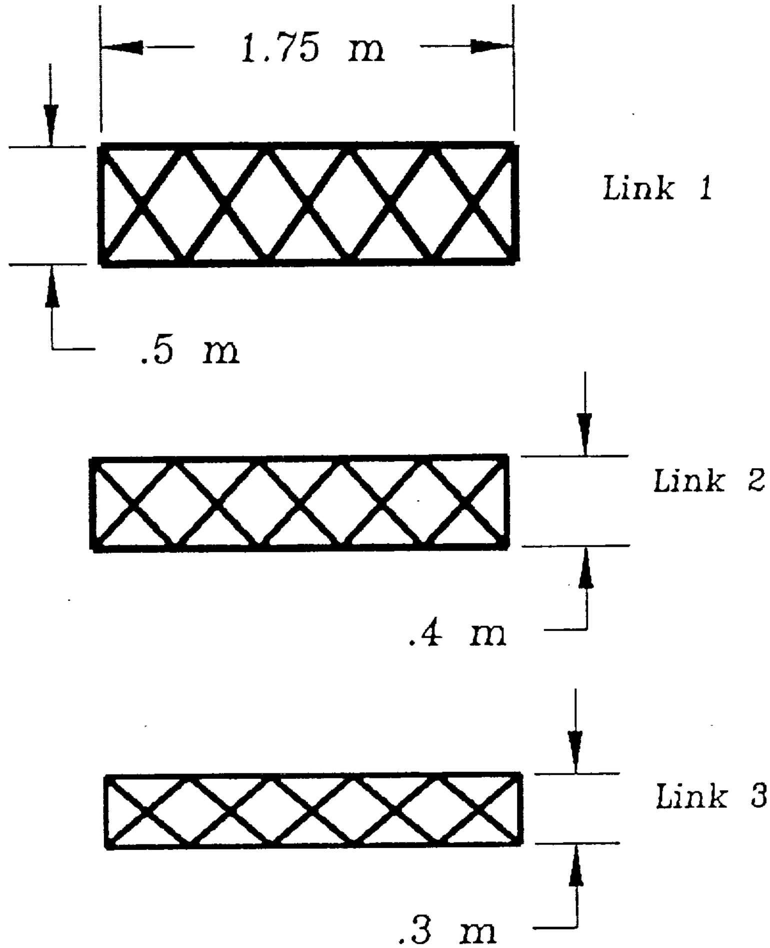


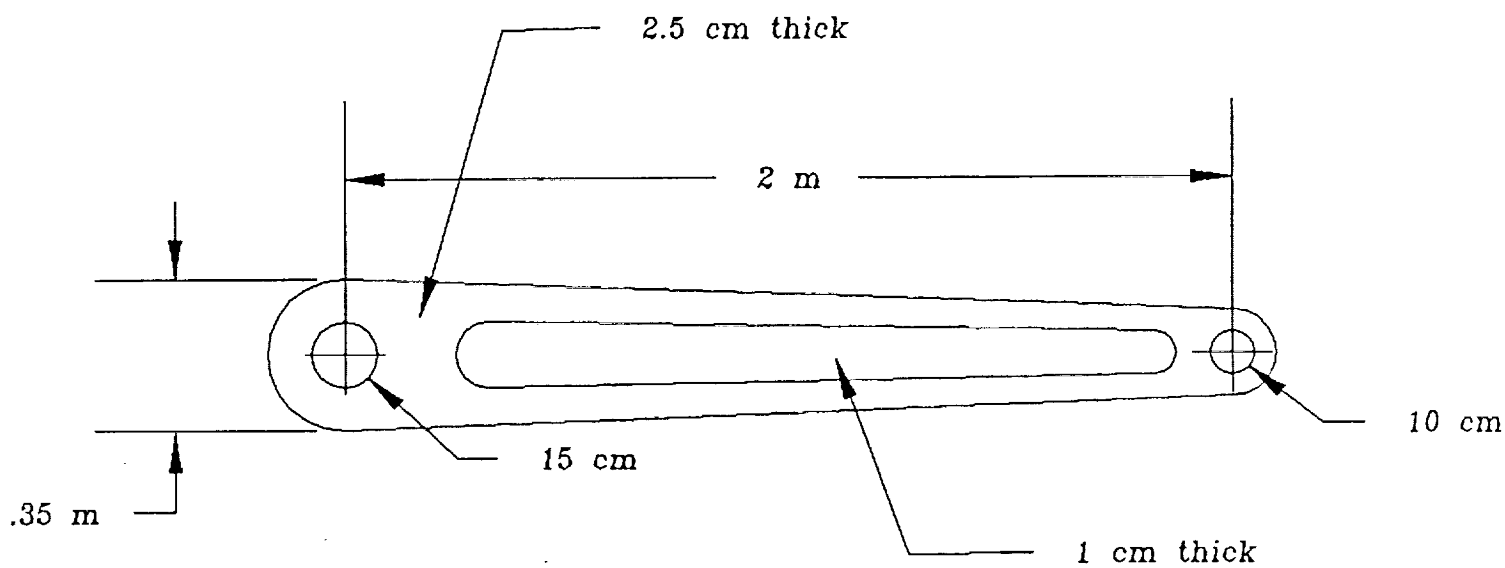


Appendix C

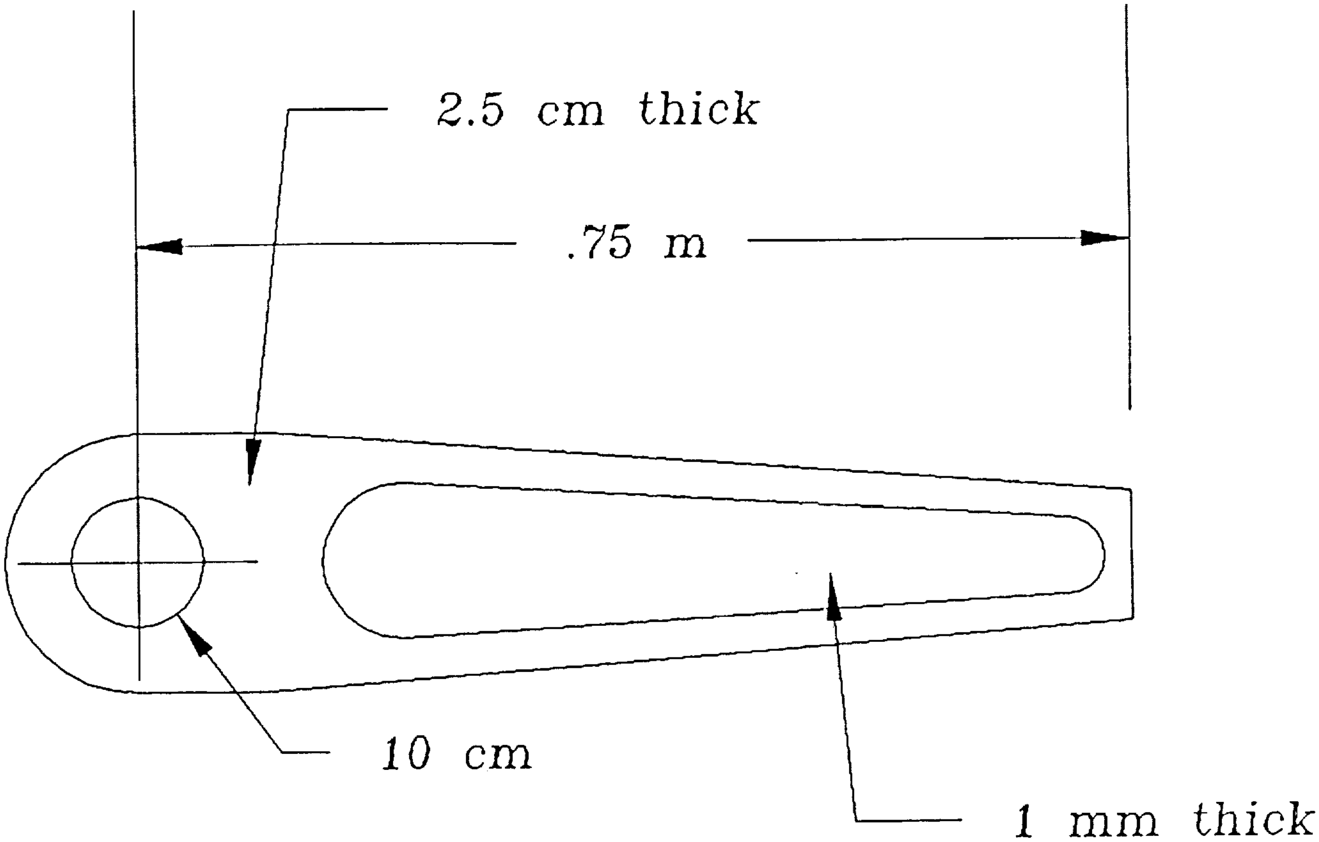
ERCOS Link Drawings


7.6 meters
4.85 meters
2.75 meters


1.75 m
Link 1
.5 m
Link 2
.4 m
Link 3
.3 m



link 4



Link 5

Appendix D

Pal2 Computer Modeling

```
TITLE LATTICE 1
NODAL POINT LOCATIONS 1
1  0, 0, 0  THROUGH 6 1.75, 0, 0
7  0, 0.4618802, 0 THROUGH 12 1.75, 0.4618802, 0
13 0, 0.2, 0.4  THROUGH 18 1.75, 0.2, 0.4
--BLANK LINE--
MATERIAL PROPERTIES 7.2e10 2.7E10 2.8E3 0.33 4.1E8 2.3E-5 2.932E2
BEAM TYPE 3, 0.035, 0.02
DO CONNECT 1 2 THROUGH 5 6  STEP 1 1
DO CONNECT 7 8 THROUGH 11 12 STEP 1 1
DO CONNECT 13 14 THROUGH 17 18 STEP 1 1
DO CONNECT 1 14 THROUGH 5 18 STEP 1 1
DO CONNECT 2 13 THROUGH 6 17 STEP 1 1
DO CONNECT 7 14 THROUGH 11 18 STEP 1 1
DO CONNECT 8 13 THROUGH 12 17 STEP 1 1
DO CONNECT 1 8 THROUGH 5 12 STEP 1 1
DO CONNECT 2 7 THROUGH 6 11 STEP 1 1
CONNECT 1 TO 13
CONNECT 1 TO 7
CONNECT 7 TO 13
CONNECT 6 TO 12
CONNECT 12 TO 18
CONNECT 6 TO 18
ZERO 1
TA OF 1
TA OF 7
TA OF 13
--BLANK LINE--
END DEFINITION
```

```
TITLE LATTICE 2
NODAL POINT LOCATIONS 1
1  0, 0, 0  THROUGH 6 1.75, 0, 0
7  0, 0.4041452, 0 THROUGH 12 1.75, 0.4041452, 0
13 0, 0.1525, 0.35  THROUGH 18 1.75, 0.1525, 0.35
--BLANK LINE--
MATERIAL PROPERTIES 7.2e10 2.7E10 2.8E3 0.33 4.1E8 2.3E-5 2.932E2
BEAM TYPE 3, 0.03, 0.0175
DO CONNECT 1 2 THROUGH 5 6  STEP 1 1
DO CONNECT 7 8 THROUGH 11 12 STEP 1 1
DO CONNECT 13 14 THROUGH 17 18 STEP 1 1
DO CONNECT 1 14 THROUGH 5 18 STEP 1 1
DO CONNECT 2 13 THROUGH 6 17 STEP 1 1
DO CONNECT 7 14 THROUGH 11 18 STEP 1 1
DO CONNECT 8 13 THROUGH 12 17 STEP 1 1
DO CONNECT 1 8 THROUGH 5 12 STEP 1 1
DO CONNECT 2 7 THROUGH 6 11 STEP 1 1
CONNECT 1 TO 13
CONNECT 1 TO 7
CONNECT 7 TO 13
CONNECT 6 TO 12
CONNECT 12 TO 18
CONNECT 6 TO 18
ZERO 1
TA OF 1
TA OF 7
TA OF 13
--BLANK LINE--
END DEFINITION
```

```
TITLE LATTICE 3
NODAL POINT LOCATIONS 1
1  0, 0, 0  THROUGH 6 1.75, 0, 0
7  0, 0.3464102, 0 THROUGH 12 1.75, 0.3464102, 0
13 0, 0.15, 0.3  THROUGH 18 1.75, 0.15, 0.3
--BLANK LINE--
MATERIAL PROPERTIES 7.2e10 2.7E10 2.8E3 0.33 4.1E8 2.3E-5 2.932E2
BEAM TYPE 3, 0.025, 0.015
DO CONNECT 1 2 THROUGH 5 6  STEP 1 1
DO CONNECT 7 8 THROUGH 11 12 STEP 1 1
DO CONNECT 13 14 THROUGH 17 18 STEP 1 1
DO CONNECT 1 14 THROUGH 5 18 STEP 1 1
DO CONNECT 2 13 THROUGH 6 17 STEP 1 1
DO CONNECT 7 14 THROUGH 11 18 STEP 1 1
DO CONNECT 8 13 THROUGH 12 17 STEP 1 1
DO CONNECT 1 8 THROUGH 5 12 STEP 1 1
DO CONNECT 2 7 THROUGH 6 11 STEP 1 1
CONNECT 1 TO 13
CONNECT 1 TO 7
CONNECT 7 TO 13
CONNECT 6 TO 12
CONNECT 12 TO 18
CONNECT 6 TO 18
ZERO 1
TA OF 1
TA OF 7
TA OF 13
--BLANK LINE--
END DEFINITION
```

TITLE Link 4 MSC/mod

NODAL POINT LOCATIONS

1	2.7	0.574998	0.0
2	0.699998	0.6	0.0
3	0.699998	0.699998	0.0
4	2.7	0.625	0.0
5	0.699998	0.349999	0.0
6	2.7	0.425	0.0
7	0.699998	0.449999	0.0
8	0.744084	0.464324	0.0
9	0.823773	0.35464	0.0
10	0.771327	0.501824	0.0
11	1.024999	0.4194	0.0
12	0.771327	0.548174	0.0
13	1.024999	0.630599	0.0
14	0.744084	0.585676	0.0
15	0.823773	0.695357	0.0
16	0.655915	0.585676	0.0
17	0.597136	0.666576	0.0
18	0.628669	0.548174	0.0
19	0.533563	0.579078	0.0
20	0.628669	0.501824	0.0
21	0.533563	0.470921	0.0
22	0.655915	0.464324	0.0
23	0.597136	0.383421	0.0
24	1.024999	0.524999	0.0
25	1.024999	0.362188	0.0
26	0.971966	0.471967	0.0
27	0.949998	0.524999	0.0
28	0.971966	0.578032	0.0
29	1.024999	0.687811	0.0
30	0.902944	0.59094	0.0
31	0.902944	0.45906	0.0
32	0.866433	0.579078	0.0
33	0.866433	0.470921	0.0
34	2.7	0.474999	0.0
35	2.729388	0.484548	0.0
36	2.758779	0.444098	0.0
37	2.747553	0.509549	0.0
38	2.795104	0.494098	0.0
39	2.747553	0.540449	0.0
40	2.795104	0.555902	0.0
41	2.729388	0.565451	0.0
42	2.758779	0.605902	0.0
43	2.670609	0.565451	0.0
44	2.625309	0.627801	0.0
45	2.652446	0.540449	0.0
46	2.574608	0.565742	0.0
47	2.652446	0.509549	0.0
48	2.574608	0.484258	0.0
49	2.670609	0.484548	0.0
50	2.625309	0.422199	0.0
51	2.574608	0.629701	0.0
52	2.574608	0.420298	0.0
53	2.524606	0.524999	0.0
54	2.524606	0.474999	0.0
55	2.559962	0.489645	0.0
56	2.574608	0.524999	0.0
57	2.559962	0.560355	0.0
58	2.524606	0.574998	0.0

```
  59 1.024999 0.6      0.0
  60 2.574608 0.574166 0.0
  61 1.024999 0.449999 0.0
  62 2.574608 0.475834 0.0
  63 0.949998 0.690625 0.0
  64 0.949998 0.359375 0.0
  65 0.949998 0.60623  0.0
  66 0.949998 0.443769 0.0
  67 2.2      0.64375  0.0
  68 2.2      0.40625  0.0
  69 1.375    0.674687 0.0
  70 1.375    0.375313 0.0
  71 1.799749 0.658759 0.0
  72 1.79995  0.391247 0.0
  73 1.375    0.594165 0.0
  74 1.799803 0.587082 0.0
  75 2.2      0.580411 0.0
  76 1.375    0.455835 0.0
  77 1.799896 0.462918 0.0
  78 2.2      0.469588 0.0
  79 0.850162 0.660552 0.0
  80 0.850162 0.389447 0.0
  81 2.640409 0.607016 0.0
  82 2.640409 0.442981 0.0
  83 0.79721  0.658797 0.0
  84 0.79721  0.391201 0.0
--BLANK LINE--
ZERO 1
TZ     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15
TZ    16   17   18   19   20   21   22   23   24   25   26   27   28   29   30
TZ    31   32   33   34   35   36   37   38   39   40   41   42   43   44   45
TZ    46   47   48   49   50   51   52   53   54   55   56   57   58   59   60
TZ    61   62   63   64   65   66   67   68   69   70   71   72   73   74   75
TZ    76   77   78   79   80   81   82
RX     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15
RX    16   17   18   19   20   21   22   23   24   25   26   27   28   29   30
RX    31   32   33   34   35   36   37   38   39   40   41   42   43   44   45
RX    46   47   48   49   50   51   52   53   54   55   56   57   58   59   60
RX    61   62   63   64   65   66   67   68   69   70   71   72   73   74   75
RX    76   77   78   79   80   81   82
RY     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15
RY    16   17   18   19   20   21   22   23   24   25   26   27   28   29   30
RY    31   32   33   34   35   36   37   38   39   40   41   42   43   44   45
RY    46   47   48   49   50   51   52   53   54   55   56   57   58   59   60
RY    61   62   63   64   65   66   67   68   69   70   71   72   73   74   75
RY    76   77   78   79   80   81   82
RZ     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15
RZ    16   17   18   19   20   21   22   23   24   25   26   27   28   29   30
RZ    31   32   33   34   35   36   37   38   39   40   41   42   43   44   45
RZ    46   47   48   49   50   51   52   53   54   55   56   57   58   59   60
RZ    61   62   63   64   65   66   67   68   69   70   71   72   73   74   75
RZ    76   77   78   79   80   81   82
--BLANK LINE--
 MATERIAL   7.20000E+10  2.70000E+10  2.80000E+03  1.30000E-01  4.10000E+08 +
  2.30000E-05  2.93200E+02
QUAD   1  0 0.025      9.99E-5
CONNECT     3 TO    2 TO   16 TO    17
CONNECT    17 TO   19 TO   18 TO    16
CONNECT    19 TO   18 TO   20 TO    21
CONNECT    21 TO   20 TO   22 TO    23
```

```
CONNECT   56 TO   53 TO   55
CONNECT   53 TO   55 TO   54
END DEFINITION
```

TITLE Link 5 MSC/MOD

NODAL POINT LOCATIONS

1	0.3	0.449999	0.0
2	0.3	0.4	0.0
3	0.264645	0.464645	0.0
4	0.229289	0.429289	0.0
5	0.25	0.5	0.0
6	0.2	0.5	0.0
7	0.264645	0.535354	0.0
8	0.229289	0.570711	0.0
9	0.3	0.55	0.0
10	0.3	0.6	0.0
11	0.335355	0.464645	0.0
12	0.4	0.4	0.0
13	0.349999	0.5	0.0
14	0.44	0.5	0.0
15	0.335355	0.535354	0.0
16	0.4	0.6	0.0
17	0.440625	0.596875	0.0
18	0.440625	0.403124	0.0
19	0.370711	0.570711	0.0
20	0.4	0.5	0.0
21	0.370711	0.429289	0.0
22	0.6	0.584613	0.0
23	0.6	0.415385	0.0
24	0.699998	0.576923	0.0
25	0.699998	0.423076	0.0
26	0.8	0.56923	0.0
27	0.8	0.430769	0.0
28	0.899999	0.561537	0.0
29	0.899999	0.438461	0.0
30	1.	0.553846	0.0
31	1.	0.529999	0.0
32	0.5	0.592306	0.0
33	0.5	0.56	0.0
34	0.5	0.5	0.0
35	0.6	0.5	0.0
36	0.699998	0.5	0.0
37	0.8	0.5	0.0
38	0.899999	0.5	0.0
39	1.	0.5	0.0
40	1.049999	0.5	0.0
41	1.049999	0.449999	0.0
42	1.049999	0.55	0.0
43	0.5	0.407691	0.0
44	1.	0.446154	0.0
45	0.5	0.44	0.0
46	1.	0.47	0.0
47	0.6	0.554	0.0
48	0.6	0.446	0.0
49	0.699998	0.547999	0.0
50	0.699998	0.451999	0.0
51	0.8	0.542	0.0
52	0.8	0.458	0.0
53	0.899999	0.536	0.0
54	0.899999	0.463999	0.0
55	0.457574	0.457574	0.0
56	0.457574	0.542424	0.0
57	1.029999	0.5	0.0
58	1.021213	0.478787	0.0

```
  59 1.021213 0.521213 0.0
  60 1.035606 0.535606 0.0
  61 1.035606 0.464393 0.0
 --BLANK LINE--
  MATERIAL    7.20000E+10  2.70000E+10  2.80000E+03  1.30000E-
  2.30000E-05  2.93200E+02
QUAD   1  0  0.025
CONNECT   10 TO   9 TO   7 TO   8
CONNECT    7 TO   5 TO   6 TO   8
CONNECT    6 TO   5 TO   3 TO   4
CONNECT    4 TO   3 TO   1 TO   2
CONNECT   11 TO  21 TO   2 TO   1
CONNECT   13 TO  20 TO  21 TO  11
CONNECT   13 TO  20 TO  19 TO  15
CONNECT   10 TO  19 TO  15 TO   9
CONNECT   16 TO  17 TO  14 TO  20
CONNECT   12 TO  18 TO  14 TO  20
CONNECT   55 TO  45 TO  43 TO  18
CONNECT   17 TO  32 TO  33 TO  56
CONNECT   32 TO  22 TO  47 TO  33
CONNECT   43 TO  23 TO  48 TO  45
CONNECT   22 TO  24 TO  49 TO  47
CONNECT   23 TO  25 TO  50 TO  48
CONNECT   24 TO  26 TO  51 TO  49
CONNECT   50 TO  52 TO  27 TO  25
CONNECT   26 TO  28 TO  53 TO  51
CONNECT   27 TO  29 TO  54 TO  52
CONNECT   28 TO  30 TO  31 TO  53
CONNECT   54 TO  46 TO  44 TO  29
CONNECT   30 TO  60 TO  59 TO  31
CONNECT   60 TO  40 TO  57 TO  59
CONNECT   46 TO  58 TO  61 TO  44
CONNECT   57 TO  40 TO  61 TO  58
TRIANGULAR   1  2  0.025
CONNECT   16 TO  20 TO  19
CONNECT   10 TO  16 TO  19
CONNECT   12 TO  20 TO  21
CONNECT    2 TO  12 TO  21
CONNECT   17 TO  56 TO  14
CONNECT   14 TO  55 TO  18
CONNECT   30 TO  42 TO  60
CONNECT   42 TO  60 TO  40
CONNECT   40 TO  41 TO  61
CONNECT   44 TO  41 TO  61
TRIANGULAR   1  2  0.005
CONNECT   33 TO  34 TO  56
CONNECT   56 TO  34 TO  14
CONNECT   45 TO  34 TO  55
CONNECT   55 TO  34 TO  14
CONNECT   31 TO  39 TO  59
CONNECT   59 TO  39 TO  57
CONNECT   46 TO  39 TO  58
CONNECT   58 TO  39 TO  57
QUAD   1  0  0.005
CONNECT   51 TO  53 TO  38 TO  37
CONNECT   33 TO  47 TO  35 TO  34
CONNECT   47 TO  49 TO  36 TO  35
CONNECT   49 TO  51 TO  37 TO  36
CONNECT   45 TO  48 TO  35 TO  34
CONNECT   48 TO  50 TO  36 TO  35
```

```
CONNECT    22  TO    23  TO     5  TO     7
CONNECT     8  TO     9  TO    31  TO    10
CONNECT    10  TO    33  TO    32  TO    12
CONNECT    12  TO    14  TO    15  TO    30
CONNECT    63  TO    29  TO    13  TO    65
CONNECT    66  TO    11  TO    25  TO    64
CONNECT    65  TO    13  TO    59  TO    28
CONNECT    26  TO    61  TO    11  TO    66
CONNECT    29  TO    69  TO    73  TO    59
CONNECT    61  TO    76  TO    70  TO    25
CONNECT    76  TO    77  TO    72  TO    70
CONNECT    71  TO    67  TO    75  TO    74
CONNECT    77  TO    78  TO    68  TO    72
CONNECT    69  TO    73  TO    74  TO    71
CONNECT    67  TO    51  TO    60  TO    75
CONNECT    78  TO    62  TO    52  TO    68
CONNECT    44  TO    43  TO    45  TO    46
CONNECT    46  TO    45  TO    47  TO    48
CONNECT    48  TO    47  TO    49  TO    50
CONNECT    34  TO    35  TO    36  TO     6
CONNECT    37  TO    38  TO    36  TO    35
CONNECT    41  TO    39  TO    40  TO    42
CONNECT     4  TO    42  TO    41  TO     1
CONNECT    39  TO    40  TO    38  TO    37
CONNECT    81  TO     4  TO     1  TO    43
CONNECT    49  TO    34  TO     6  TO    82
CONNECT    79  TO    63  TO    65  TO    30
CONNECT    31  TO    66  TO    64  TO    80
CONNECT     7  TO     8  TO    84  TO     5
CONNECT     3  TO    83  TO    14  TO     2
TRIANGULAR     1   2  0.025     0.025     0.025       9.99E-5
CONNECT    51  TO    46  TO    44
CONNECT    48  TO    52  TO    50
CONNECT    62  TO    55  TO    54
CONNECT    62  TO    55  TO    56
CONNECT    60  TO    57  TO    56
CONNECT    60  TO    57  TO    58
CONNECT    32  TO    65  TO    27
CONNECT    27  TO    33  TO    32
CONNECT    66  TO    27  TO    33
CONNECT    65  TO    28  TO    27
CONNECT    27  TO    26  TO    66
CONNECT    63  TO    15  TO    79
CONNECT    64  TO    80  TO     9
CONNECT    44  TO     4  TO    81
CONNECT    82  TO     6  TO    50
CONNECT     3  TO    83  TO    15
CONNECT    84  TO     9  TO     5
QUAD    1   0 0.01       9.99E-5
CONNECT    59  TO    73  TO    76  TO    61
CONNECT    73  TO    74  TO    77  TO    76
CONNECT    74  TO    75  TO    78  TO    77
CONNECT    75  TO    58  TO    54  TO    78
TRIANGULAR     1   2  0.01      0:01      0.01        9.99E-5
CONNECT    28  TO    59  TO    24
CONNECT    24  TO    27  TO    28
CONNECT    27  TO    24  TO    26
CONNECT    24  TO    26  TO    61
CONNECT    58  TO    53  TO    57
CONNECT    56  TO    53  TO    57
```

```
CONNECT   36 TO   37 TO   52 TO   50
CONNECT   52 TO   54 TO   38 TO   37
CONNECT   53 TO   31 TO   39 TO   38
CONNECT   54 TO   46 TO   39 TO   38
ZERO 11
TZ 1 THROUGH 61
RA 1 THROUGH 61
--BLANK LINE--
END DEFINITION
```

Loading Files for Links

```
    forces and moments applied 1
fz -213.2 18
fz  3236.8571 17
fz -1831.6286 6  12
--blank line--
solve
quit
```

Link 1

```
forces and moments applied 1
fz -196.32633 18
fz 1814.3547 17
fz -1103.5037 6  12
--blank line--
solve
quit
```

Link 2

```
forces and moments applied 1
fz -185.73 18
fz 1071.425 17
fz -721.4425 6  12
--blank line--
solve
quit
```

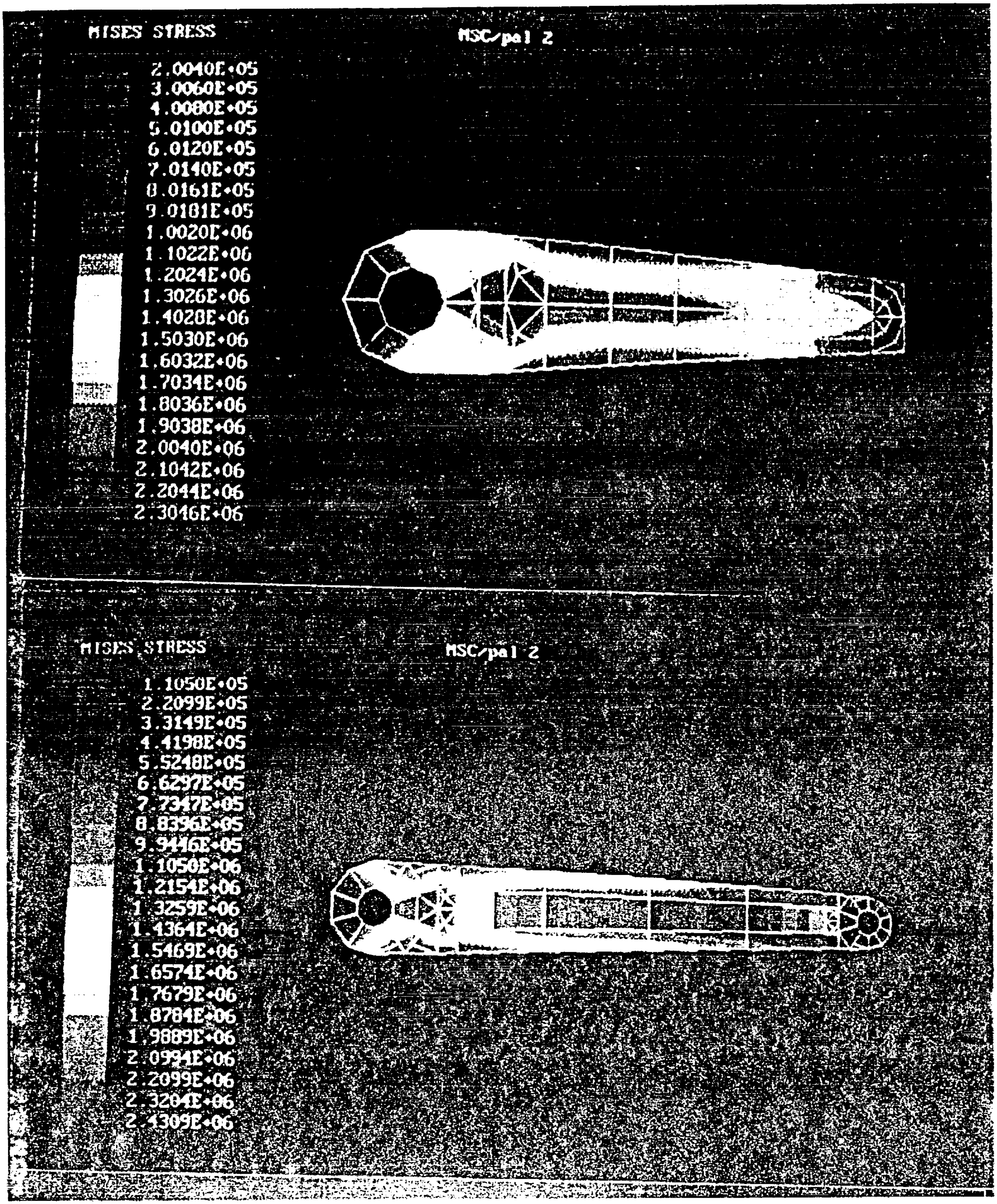
Link 3

```
FORCES AND MOMENTS APPLIED 0
FY 34 -500.0
MZ 1 -41.6667
MZ 34 -41.6667
MZ 35 -41.6667
MZ 37 -41.6667
MZ 39 -41.6667
MZ 41 -41.6667
MZ 45 -41.6667
MZ 47 -41.6667
MZ 49 -41.6667
-- BLANK LINE --
DISPLACEMENTS APPLIED 1
ALL 0 2 7 8 10 12 14 16 18 20 22
-- BLANK LINE --
SOLVE
QUIT
```

Link 4

```
FORCES AND MOMENTS APPLIED 0
FY 40 -500.0
-- BLANK LINE --
DISPLACEMENTS APPLIED 1
ALL 0 1 3 5 7 9 11 13 15
-- BLANK LINE --
SOLVE
QUIT
```

Link 5



ORIGINAL PAGE IS
OF POOR QUALITY

LINK 5 MSC/pal 2

SUBCASE: 1

NODE	X DEF.	Y DEF.	Z DEF.	X ROT.	Y ROT.	Z ROT.
1	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
2	-1.322E-06	4.176E-08	0.000E-01	0.000E-01	0.000E-01	0.000E-01
3	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
4	-3.289E-07	3.583E-07	0.000E-01	0.000E-01	0.000E-01	0.000E-01
5	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
6	-1.095E-13	2.916E-07	0.000E-01	0.000E-01	0.000E-01	0.000E-01
7	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
8	3.289E-07	3.583E-07	0.000E-01	0.000E-01	0.000E-01	0.000E-01
9	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
10	1.323E-06	4.176E-08	0.000E-01	0.000E-01	0.000E-01	0.000E-01
11	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
12	-3.383E-06	-2.344E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
13	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
14	3.115E-11	-3.618E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
15	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
16	3.383E-06	-2.344E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
17	4.356E-06	-4.003E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
18	-4.356E-06	-4.003E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
19	1.946E-06	-1.330E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
20	1.906E-11	-1.822E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
21	-1.946E-06	-1.330E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
22	8.555E-06	-1.743E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
23	-8.555E-06	-1.743E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
24	1.086E-05	-3.067E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
25	-1.086E-05	-3.067E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
26	1.240E-05	-4.808E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
27	-1.240E-05	-4.808E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
28	1.322E-05	-6.951E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
29	-1.322E-05	-6.951E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
30	1.271E-05	-9.407E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
31	6.817E-06	-9.398E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
32	6.066E-06	-7.845E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
33	3.558E-06	-7.585E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
34	5.458E-11	-7.393E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
35	8.801E-11	-1.694E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
36	1.591E-10	-3.032E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
37	1.973E-10	-4.781E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
38	2.132E-10	-6.936E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
39	2.378E-10	-9.390E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
~~40~~	~~2.401E-10~~	~~-1.064E-04~~	~~0.000E-01~~	~~0.000E-01~~	~~0.000E-01~~	~~0.000E-01~~
41	-1.178E-05	-1.063E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
42	1.178E-05	-1.063E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
43	-6.066E-06	-7.846E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
44	-1.271E-05	-9.407E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
45	-3.558E-06	-7.585E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
46	-6.816E-06	-9.398E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
47	5.347E-06	-1.714E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
48	-5.347E-06	-1.714E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
49	6.519E-06	-3.044E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
50	-6.519E-06	-3.044E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
51	7.283E-06	-4.789E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
52	-7.282E-06	-4.789E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
53	7.288E-06	-6.940E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01

ORIGINAL PAGE IS
OF POOR QUALITY

54	-7.288E-06	-6.940E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
55	-2.058E-06	-4.641E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
56	2.058E-06	-4.641E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
57	2.395E-10	-1.015E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
58	-4.932E-06	-9.930E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
59	4.932E-06	-9.930E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
60	8.358E-06	-1.028E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
61	-8.358E-06	-1.028E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01

* POINT OF MAXIMUM DEFLECTION (END POINT OF LINK)

Link #4 MSC/pal 2

SUBCASE: 1

NODE	X DEF.	Y DEF.	Z DEF.	X ROT.	Y ROT.	Z ROT.
1	1.597E-05	-3.896E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
2	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
3	3.270E-06	4.015E-08	0.000E-01	0.000E-01	0.000E-01	0.000E-01
4	3.233E-05	-3.896E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
5	-3.270E-06	4.014E-08	0.000E-01	0.000E-01	0.000E-01	0.000E-01
6	-3.216E-05	-3.904E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
7	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
8	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
9	-6.529E-06	-3.683E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
10	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
11	-6.600E-06	-1.587E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
12	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
13	6.600E-06	-1.587E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
14	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
15	6.528E-06	-3.683E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
16	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
17	1.678E-06	1.067E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
18	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
19	4.640E-07	1.345E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
20	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
21	-4.641E-07	1.345E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
22	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
23	-1.678E-06	1.067E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
24	-3.068E-11	-1.530E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
25	-1.338E-05	-1.644E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
26	-3.375E-06	-1.177E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
27	2.528E-11	-1.028E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
28	3.375E-06	-1.177E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
29	1.338E-05	-1.644E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
30	2.470E-06	-6.761E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
31	-2.470E-06	-6.762E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
32	3.422E-06	-4.733E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
33	-3.422E-06	-4.733E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
34	-1.577E-05	-3.907E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
35	-1.294E-05	-3.999E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
36	-2.572E-05	-4.093E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
37	-5.062E-06	-4.056E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
38	-9.998E-06	-4.206E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
39	4.753E-06	-4.054E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
40	~~9.696E-06~~	~~-4.200E-04~~	~~0.000E-01~~	~~0.000E-01~~	~~0.000E-01~~	~~0.000E-01~~
41	1.282E-05	-3.993E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
42	2.609E-05	-4.090E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
43	1.303E-05	-3.799E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
44	3.292E-05	-3.653E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
45	5.150E-06	-3.741E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
46	1.320E-05	-3.492E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
47	-4.601E-06	-3.743E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
48	-1.270E-05	-3.491E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
49	-1.259E-05	-3.804E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
50	-3.292E-05	-3.655E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
51	3.339E-05	-3.490E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
52	-3.338E-05	-3.489E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01

53	-3.166E-08	-3.332E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
54	-1.587E-05	-3.327E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
55	-1.058E-05	-3.442E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
56	-1.922E-08	-3.486E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
57	1.055E-05	-3.442E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
58	1.586E-05	-3.327E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
59	5.956E-06	-1.569E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
60	1.462E-05	-3.488E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
61	-5.956E-06	-1.569E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
62	-1.462E-05	-3.488E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
63	1.026E-05	-1.013E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
64	-1.026E-05	-1.013E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
65	5.145E-06	-1.030E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
66	-5.145E-06	-1.030E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
67	3.283E-05	-2.336E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
68	-3.283E-05	-2.336E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
69	2.138E-05	-5.652E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
70	-2.138E-05	-5.651E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
71	2.896E-05	-1.337E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
72	-2.897E-05	-1.338E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
73	9.841E-06	-5.605E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
74	1.321E-05	-1.333E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
75	1.523E-05	-2.334E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
76	-9.841E-06	-5.605E-05	0.000E-01	0.000E-01	0.000E-01	0.000E-01
77	-1.321E-05	-1.334E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
78	-1.523E-05	-2.334E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
79	6.890E-06	-4.620E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
80	-6.890E-06	-4.620E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
81	2.631E-05	-3.702E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
82	-2.618E-05	-3.706E-04	0.000E-01	0.000E-01	0.000E-01	0.000E-01
83	3.376E-06	-2.566E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01
84	-3.376E-06	-2.566E-06	0.000E-01	0.000E-01	0.000E-01	0.000E-01

* POINT OF MAXIMUM DEFLECTION